衛星・地上観測とコンピュータシミュレーションによる超高層大気研究

成蹊大学

藤原　均

1．熱圏について

Atmospheric Temperature by MSISE 90

$\partial T/\partial z = 0$
Thermopause

Exosphere

Barosphere

Ionosphere

Thermosphere

turbopause

Mesosphere
Stratosphere
Troposphere

Altitude (km)

Temperature (K)

国際航空連盟
(FAI)
宇宙空間

100 km

カーマン・ライン
(Kármán line)
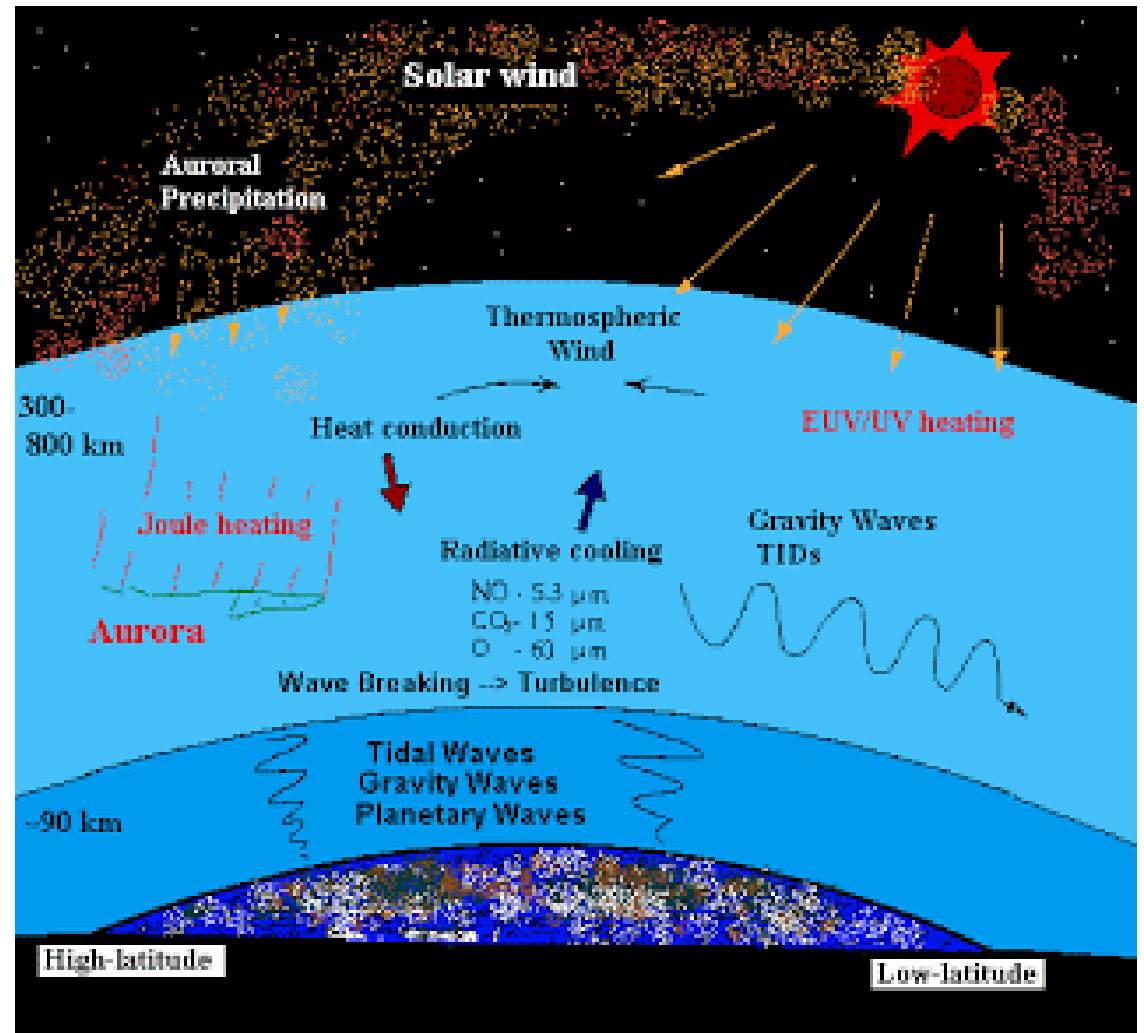
大気圏
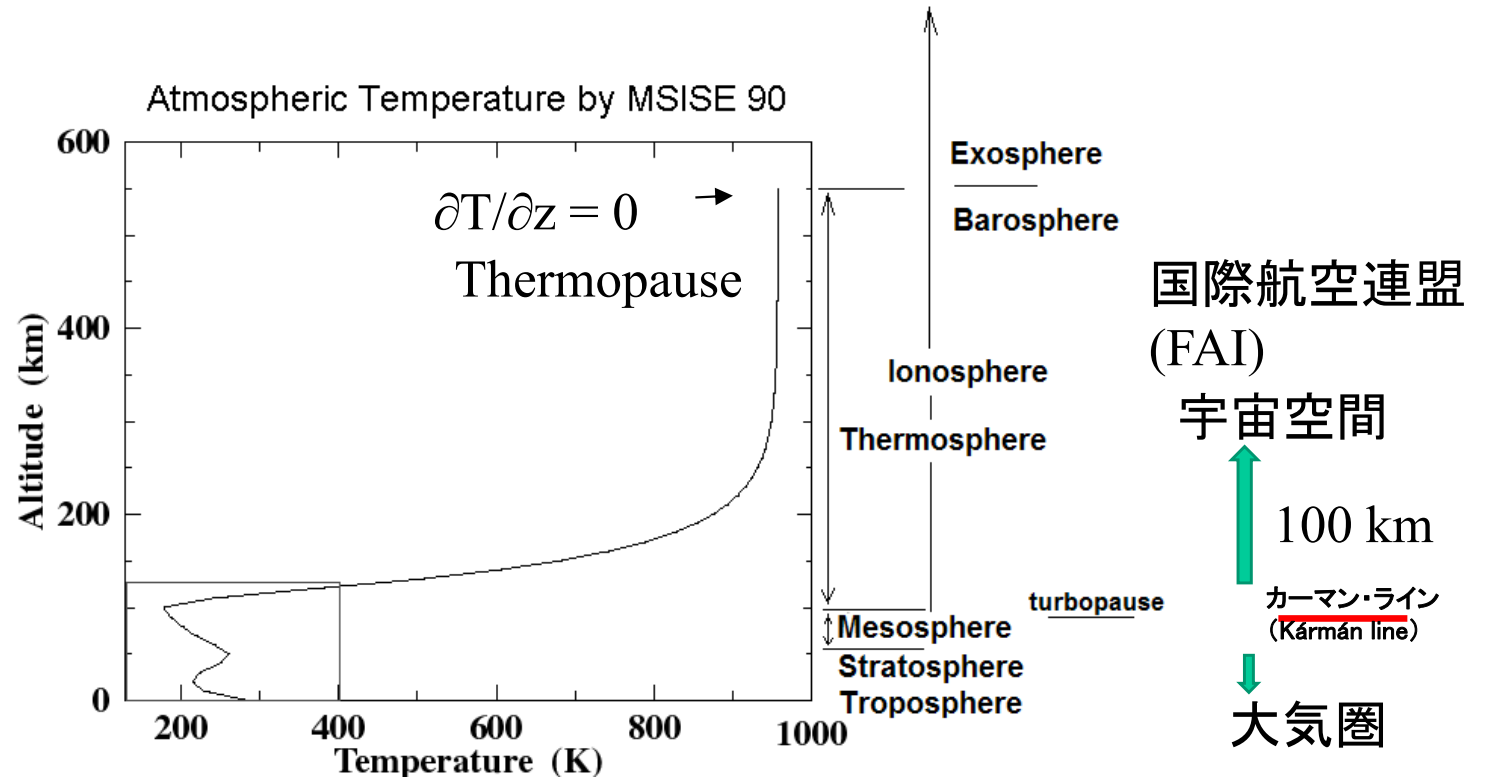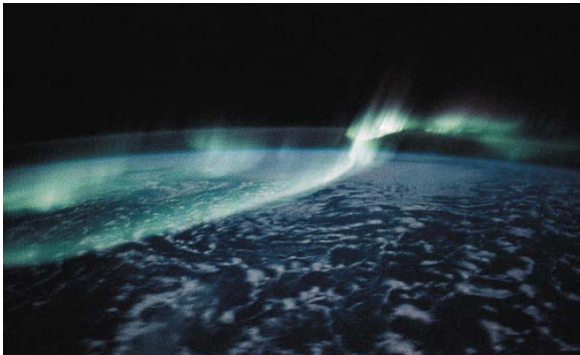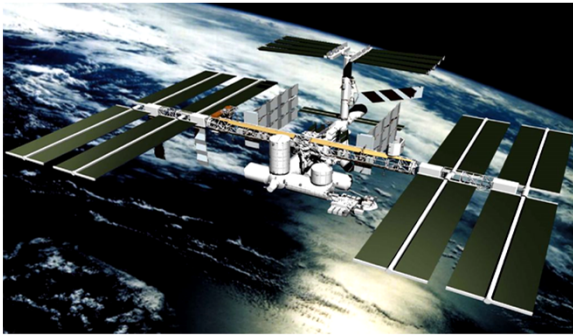
Aeronomy ＝Aero + nomy

The term aeronomy was introduced by Sydney Chapman in a Letter to the Editor of Nature (journal) entitled Some Thoughts on Nomenclature in 1946.
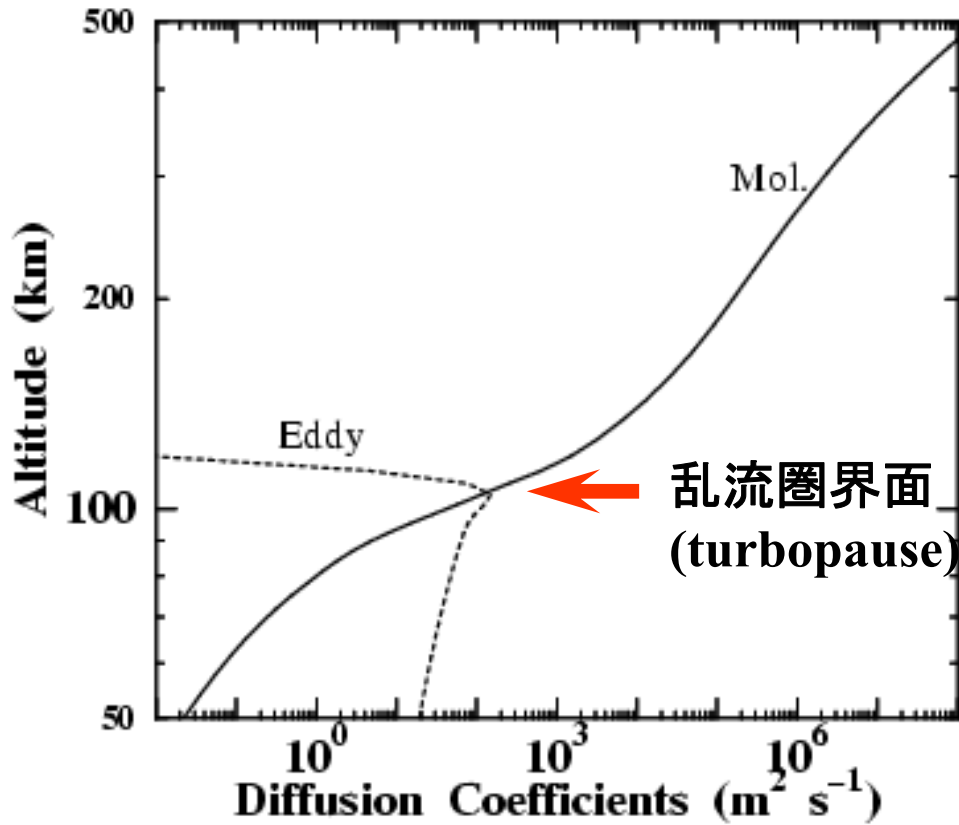
大気科学　天文学

・流体的世界＋粒子的世界
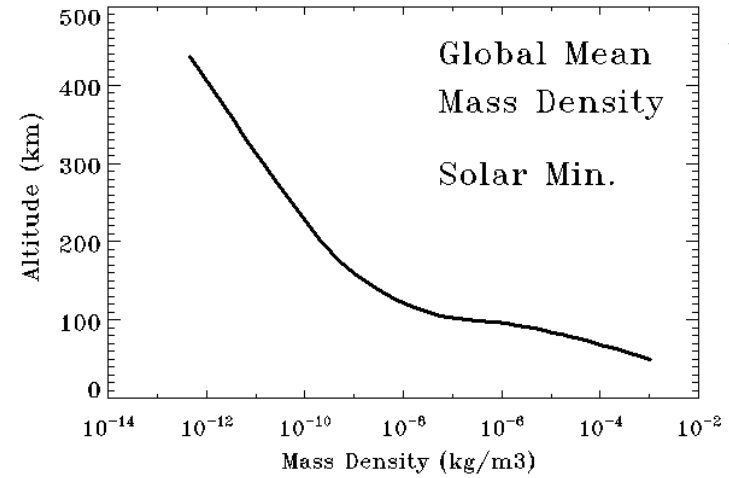(熱圏界面: スケールハイト～平均自由行程)
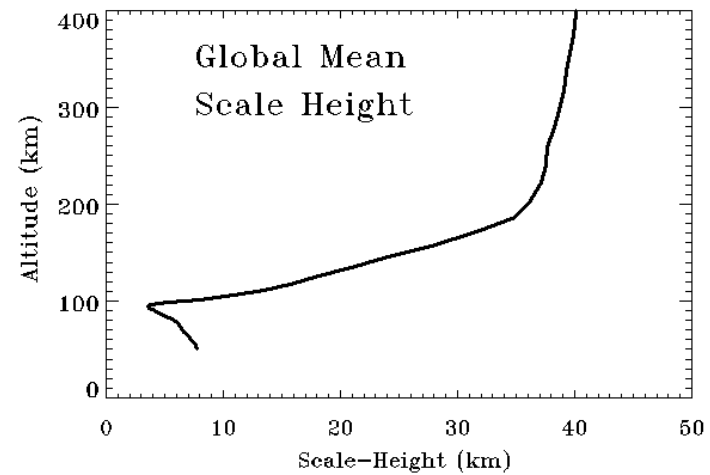・乱流から分子過程へ
・中性とプラズマが混在
・特殊な放射
　　　LTEからnon-LTEへ
・様々な大気波動
・磁気圏と下層大気からの
　エネルギー流入

（from 1D model calculation）

分子拡散(Mol)、渦拡散(Eddy)
係数の高度プロファイル。

O rich

N$_2$, O$_2$
rich

熱圏大気について

Thermosphere
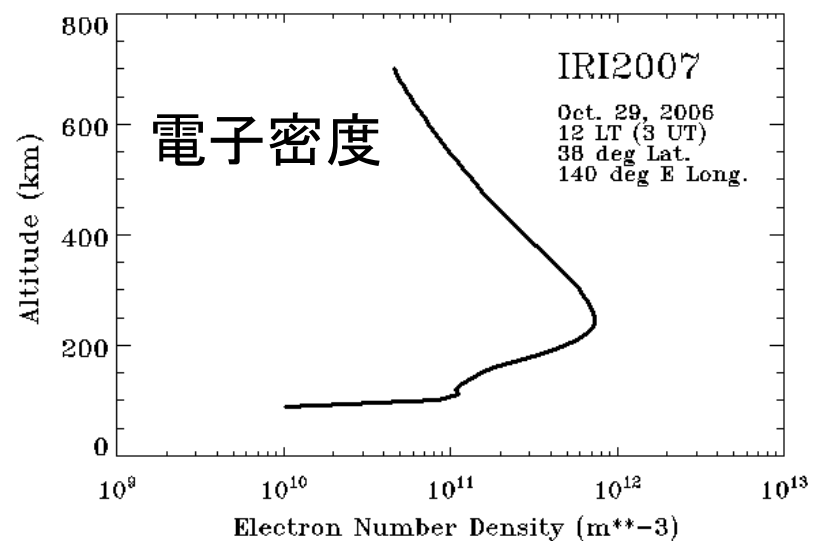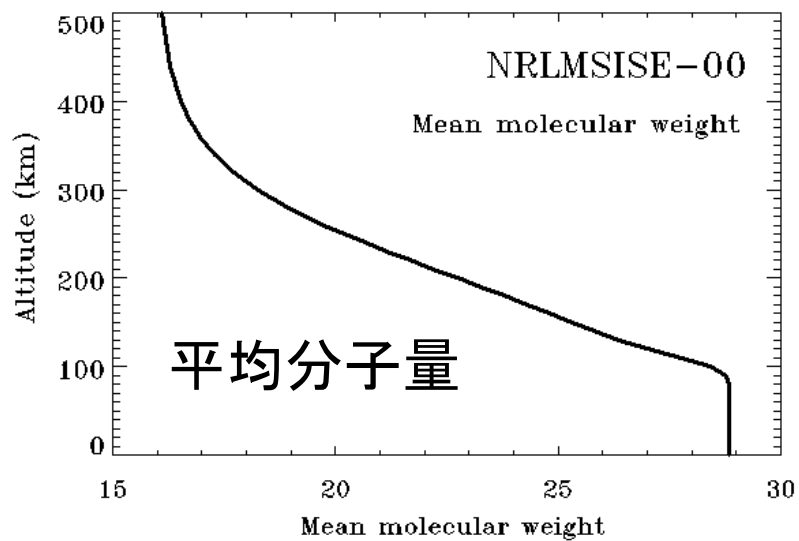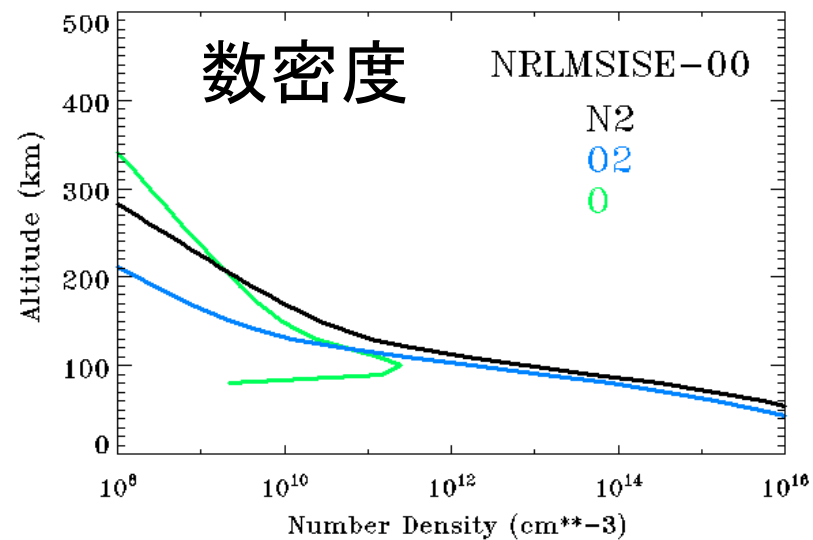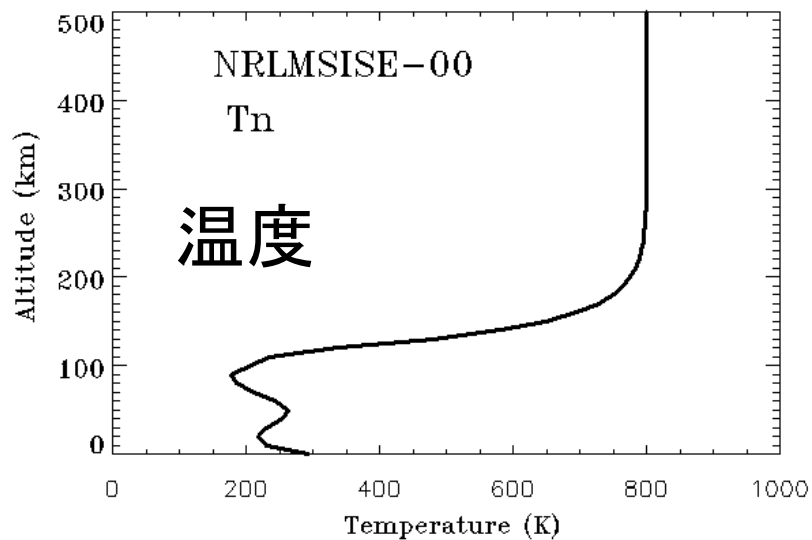
太陽活動や
オーロラ活動
による変化

質量密度
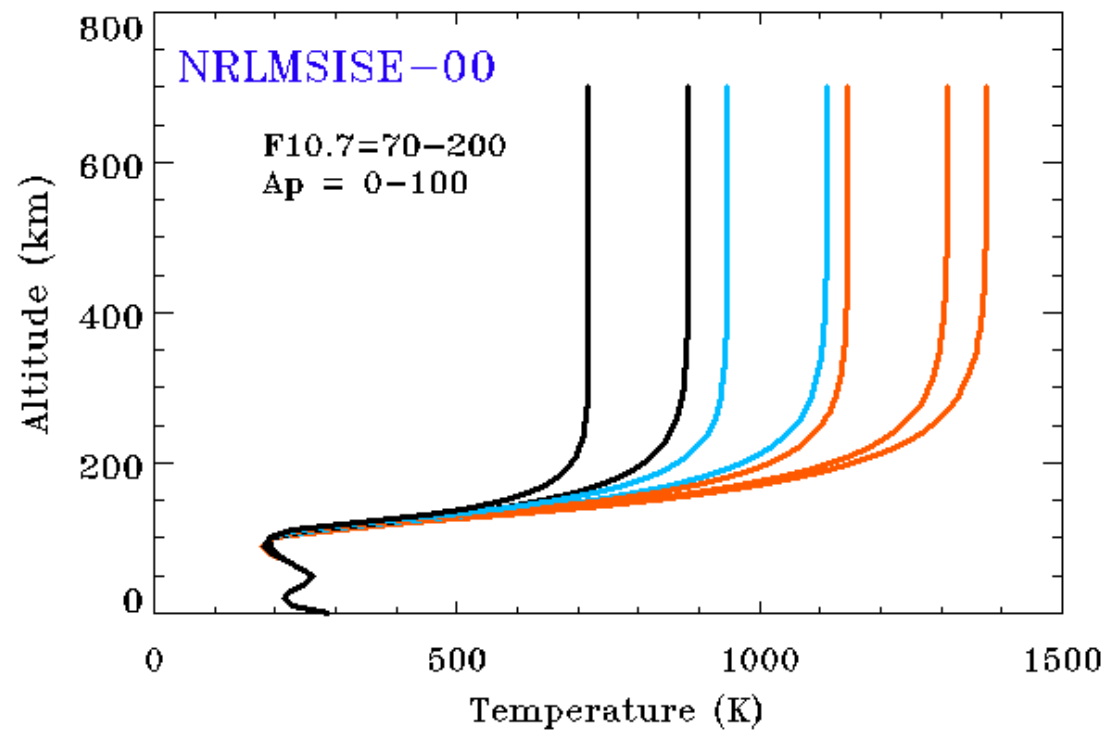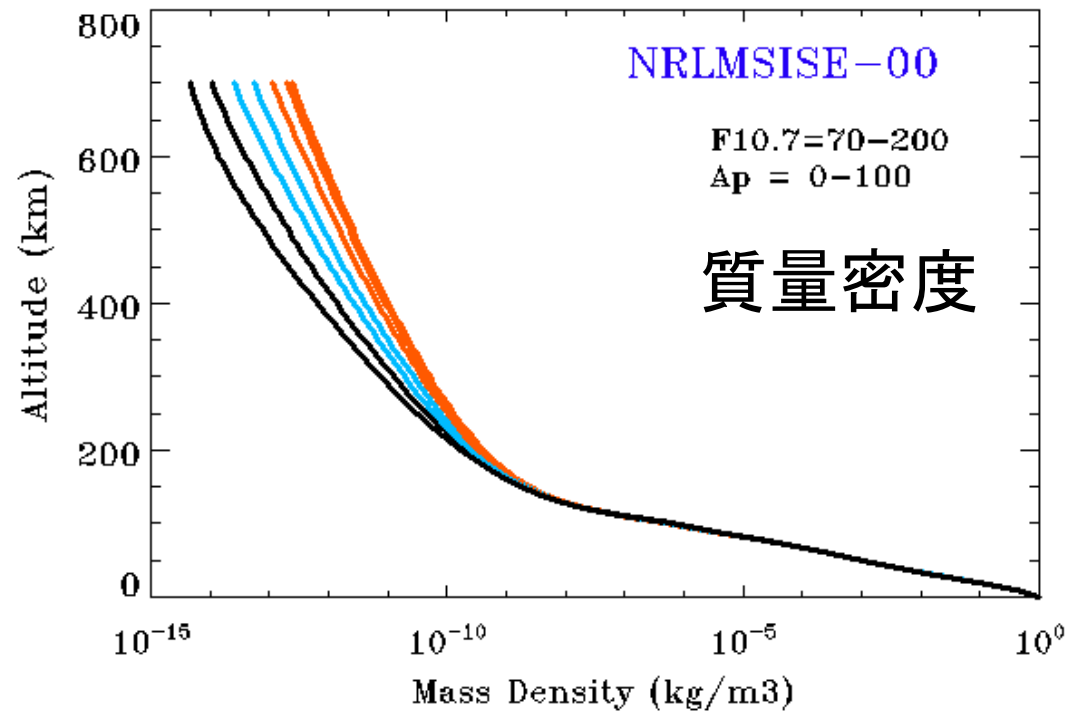
熱圏大気の子午面循環

子午面循環を2つの熱源が駆動する：赤道・・・太陽紫外線加熱、
　　極域・・・オーロラ加熱
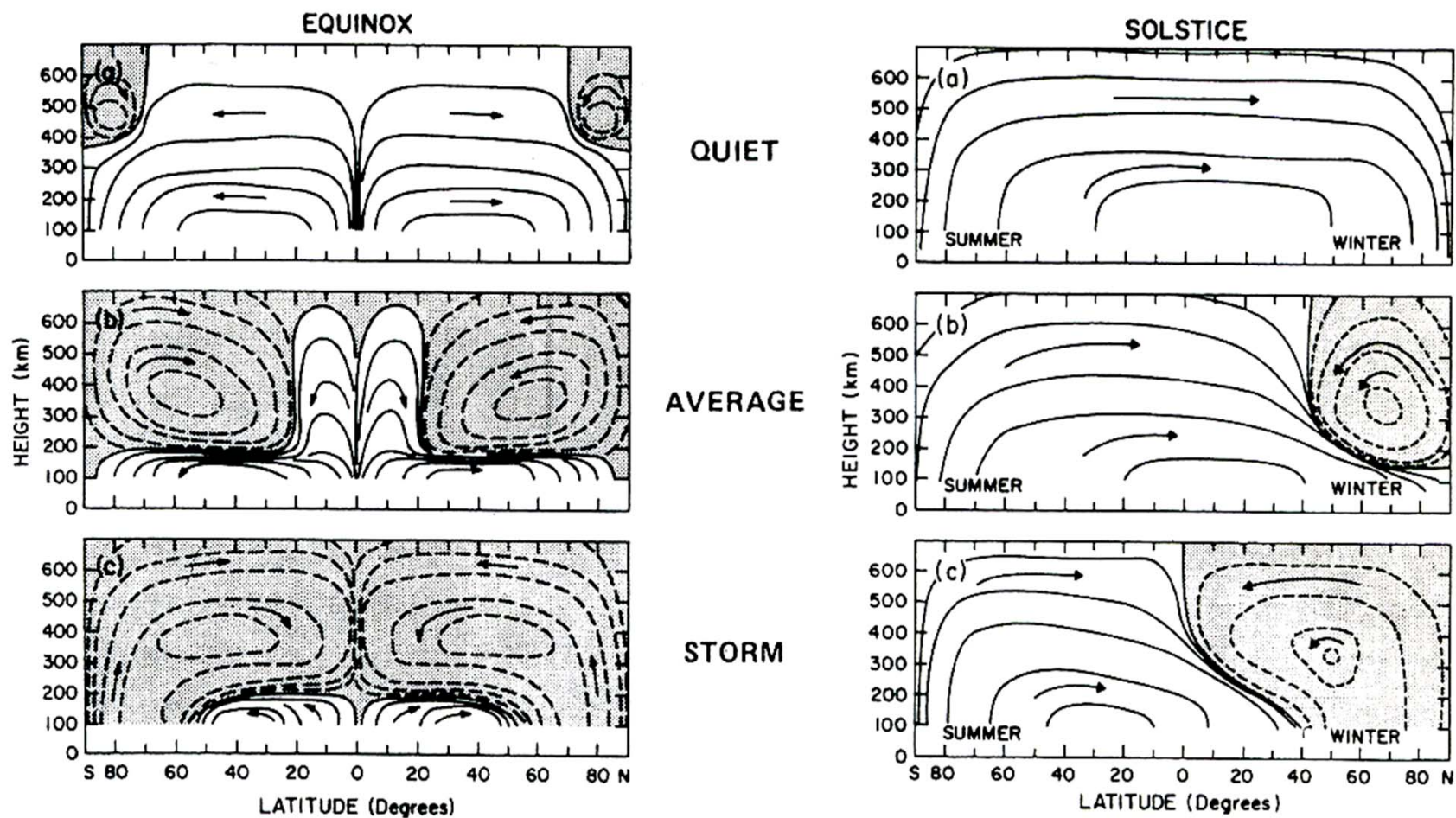
Roble (1987)

超高層大気の大循環
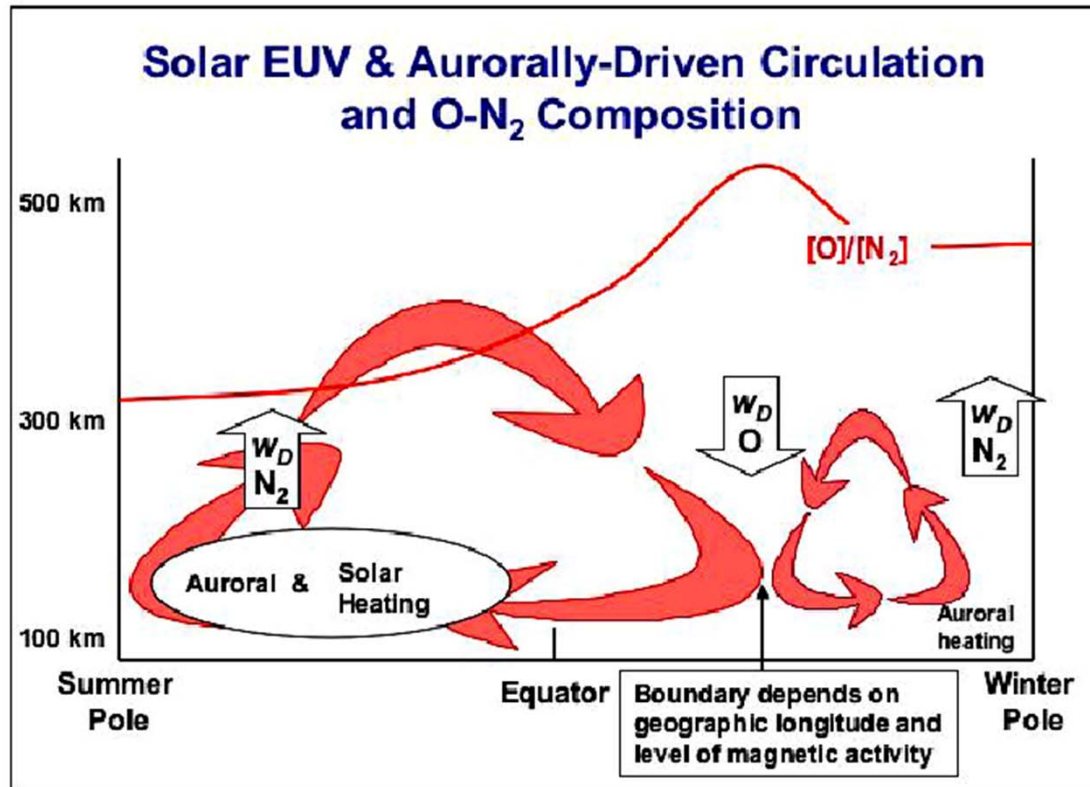
Figure 7. Same as Figure 6, with effects of high-latitude heating due to magnetospheric coupling processes.

Forbes (2007)
(Journal of Meteorological Society of Japan)

電離圏プラズマの存在下における中性大気の運動

$$\frac{d\mathbf{U}}{dt} = -2\Omega \times \mathbf{U} + g - \frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla \cdot (\mu\nabla)\mathbf{U} - \nu_{ni}(\mathbf{U} - \mathbf{V})$$

$$\left(-\nu_{ni}(\mathbf{U} - \mathbf{V}) = \frac{1}{\rho}\mathbf{J} \times \mathbf{B}\right)$$
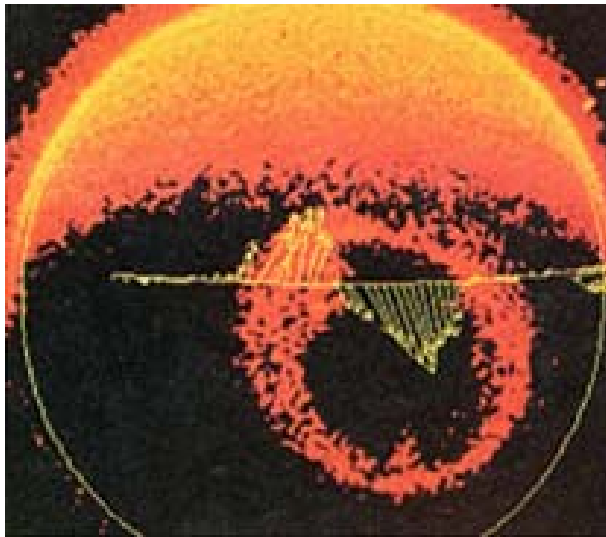
← DE1衛星による紫外
オーロラ撮像とDE2
衛星による中性風観測

(Killeen et al., 1988)

２．熱圏・電離圏モデルの開発史

英国（UCL+Shefield Univ, NOAA）と米国(NCAR)の開発競争

Fuller-Rowell et al. (1980)が熱圏大気大循環モデルの始まり。
Roble et al. (1981)が次いで発表される。

Fuller-Rowell et al. (1987)が熱圏・電離圏モデルの始まり。
Roble et al. (1988)が次いで発表される。

Timothy J. Fuller-Rowell

https://cires.colorado.edu/council-fellows/
timothy-j-fuller-rowell

Raymond G. Roble

https://www2.hao.ucar.edu/news/2014-jan/
roble-honored-bowie-medal

Fuller-Rowell et al. (1980)→ … → CTIM, CTIPe, IDEA

Roble et al. (1981) → … → TIE-GCM, TIME-GCM,
                                        WACCM-X

気象モデル→熱圏モデル→熱圏・電離圏モデル

　　→各種結合モデル
　　　熱圏。電離圏。磁気圏結合モデル
　　　全大気圏・電離圏結合モデル
　　　　（WACCM-X, IDEA, GAIAの３つのみ)

　→惑星超高層モデル（金星、火星、木星、土星、タイタン）

　→データ同化（NCAR、NOAAを中心に）

September 1968
R. E. Dickinson and J. E. Geisler
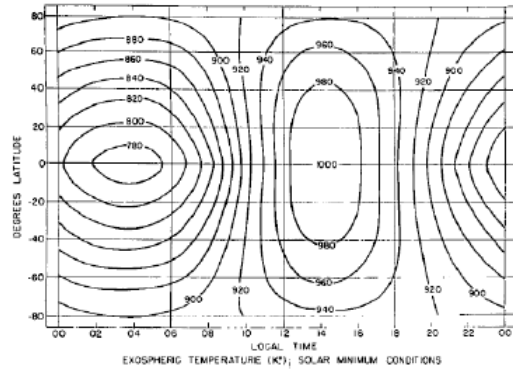
Exospheric Temperatures from Jacchia 1965 model, used with model densities to derive pressures and pressure gradients
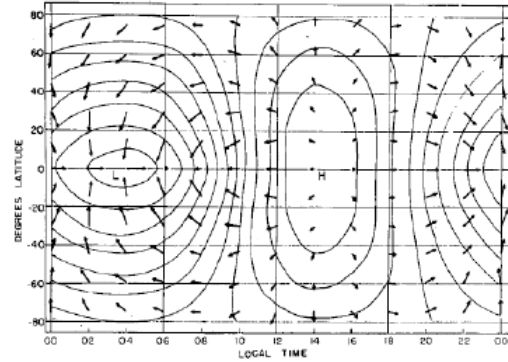
Wind vectors calculated from momentum equation with Jacchia 1965 pressure gradient forcing. Isobars are shown by solid lines

CEDAR 2007 Student Workshop, June 2007

超高層の風は等圧線を横切って吹く。

下層の風は、等圧線に沿って吹く。 (地衡風)

NCAR TGCM with tides

CTIP modeling (Rishbeth et al., 2000)

March

"quiet convection" (Kp = 2)

Shift from noon maximum due to "secondary heat source" associated with vertical motions
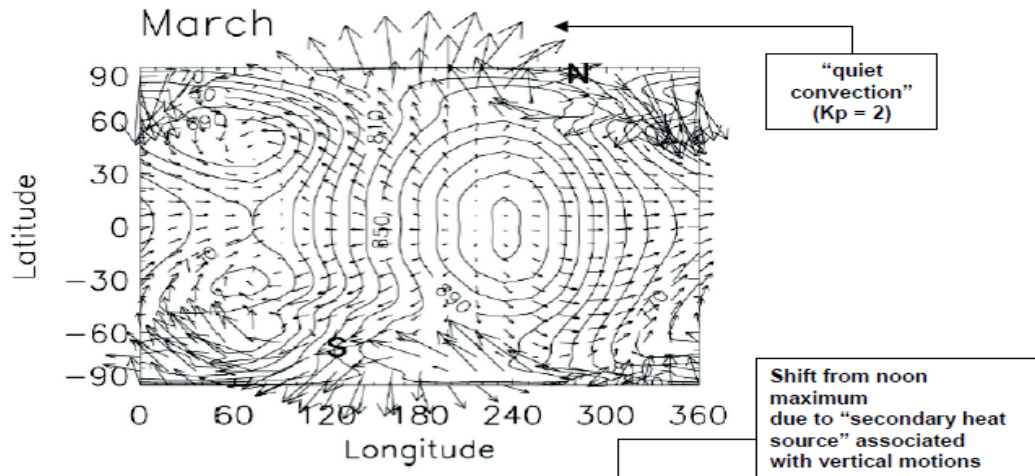
Exospheric temperatures peak near **15:30 h** local time.
Day-night temperature differences at low latitudes reach around **200 K**.
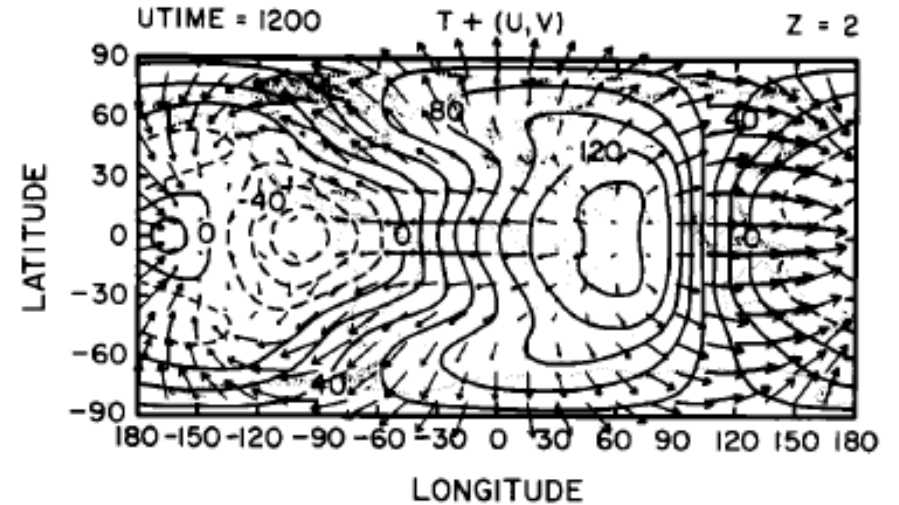
Perturbation temperatures from a constant global mean value (solid curves) and winds (arrows) at fixed pressure levels for Equinox conditions during solar minimum calculated by the TGCM with tides (Fesen et al., 1986)

超高層大気・電離圏モデルの種類

１．統計(経験)モデル

NRLMSISE-00, NRLMSIS 2.0　(超高層物理学分野での標準モデル)

International Reference Ionosphere (IRI)　(電離圏モデル)

DTM-2020,　　JB2008

Marshall Engineering Thermosphere Model (MET-2007)

２．物理モデル

TIME-GCM, TIE-GCM, WACCAM-X (NCARモデル)

CTIM, CMAT, IDEA (NOAA, UCL)

Global Assimilation of Ionospheric Measurements (GAIM)

SAMI3(電離圏：NRL）, AFRL Global Theoretical Ionospheric Model (GTIM)

Global Coupled Ionosphere Thermosphere-Electrodynamics Model
　　(Chinese model:GCITEM)

３．その他

AMIEなど　(電場/ポテンシャル分布の導出)

The Global airglow model (GLOW)

Global Scale Wave Model (GSWM) ：大気波動(潮汐)モデル

Japanese model

Based on a GCM by Japanese Meteorological Agency

Middle atmosphere GCM

Kyushu GCM (Miyahara,1991; Miyoshi,1999)

Miyoshi and Fujiwara (2003)
Whole atmosphere GCM

世界初の全大気圏モデル

Model inputs
potential data

EISCAT, MU,
EAR, PANSY,
IMAP, GPS,
SuperDARN,
FPI, Lidar, …

Ground-to-topside model
of Atmosphere and
Ionosphere for
Aeronomy (**GAIA**)
(*Jin et al.,* JGR, 2011)

2011

Kyushu Univ.
NICT
Seikei Univ.

Programs

IMAP
Ground-based
 observations
 (EISCAT-3D)
FACTORS

３．全大気圏モデル・大気圏-電離圏モデル(GAIA)

a) 12 km　　d) 134 km
b) 50 km　　e) 180 km
c) 89 km　　f) 306 km

Solar min, Geomag quiet
(Fujiwara et al., 2011)

Ground-to-topside model
of Atmosphere and Ionosphere
for Aeronomy （GAIA）

Solar wind

Radiation

Electromagnetic energy (magnetosphere)
Auroral particle
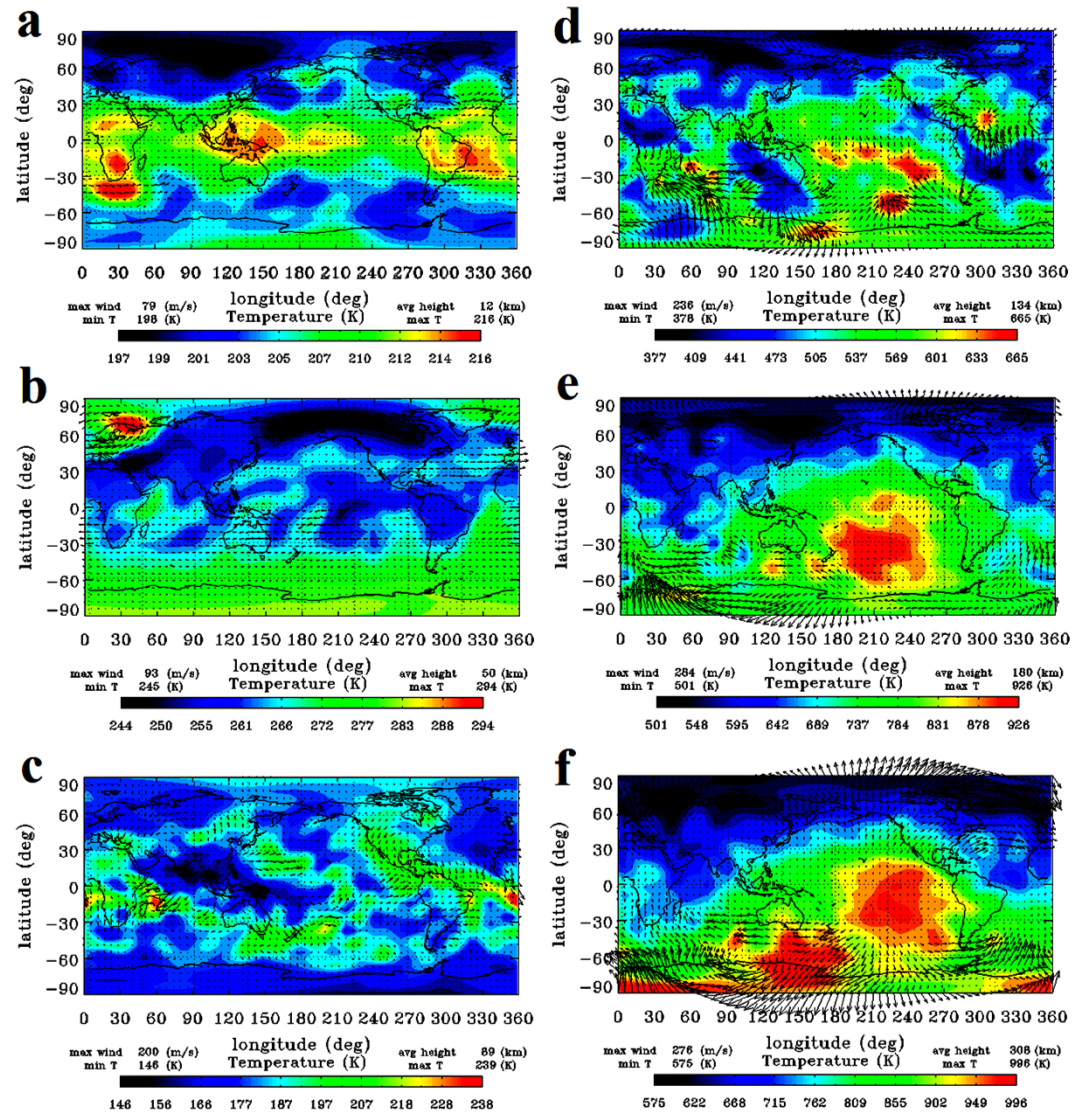
*Gaia, the goddess
of the mother earth,
was born from chaos*

ionosphere

Te, Ti, Vi
Ne, ··

[km]
~ 500-700

Thermosphere

$T, \rho, V, ..$ variations

"Cooling"

Atmospheric waves

Mesosphere

O_3
Stratosphere

GAIA

Jin et al. [2011]
Miyoshi et al. [2011]

CO_2 enhancement

Troposphere

0

Antikenmuseen,
Berlin

www.theoi.com
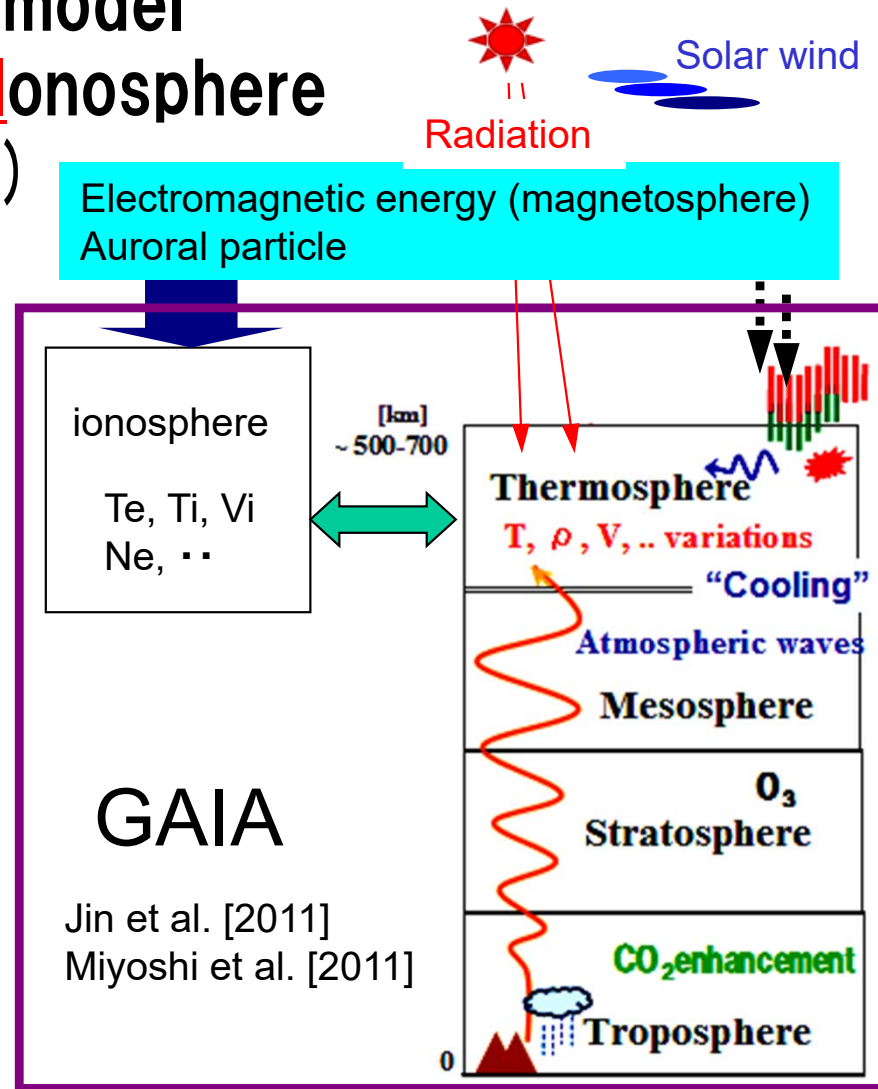
GAIA (Ground-to-topside model of Atmospheres and Ionosphere for Aeronomy)

超高層物理学

宇宙プラズマ科学

太陽活動変化
オーロラ活動変化

高度約700 km

熱圏（中性大気）

運動量交換

電離圏（電離大気）

光化学反応

中間圏

寒冷化

大気波動

成層圏

温暖化

対流圏

気象学

CO$_2$

地表

・対流圏から熱圏・電離圏まで
気象学・超高層物理学・宇宙プラズマ
科学の融合
・気象現象が上層へ及ぼす影響
・熱圏・電離圏変動の数値予報

（九州大・NICT・成蹊大）
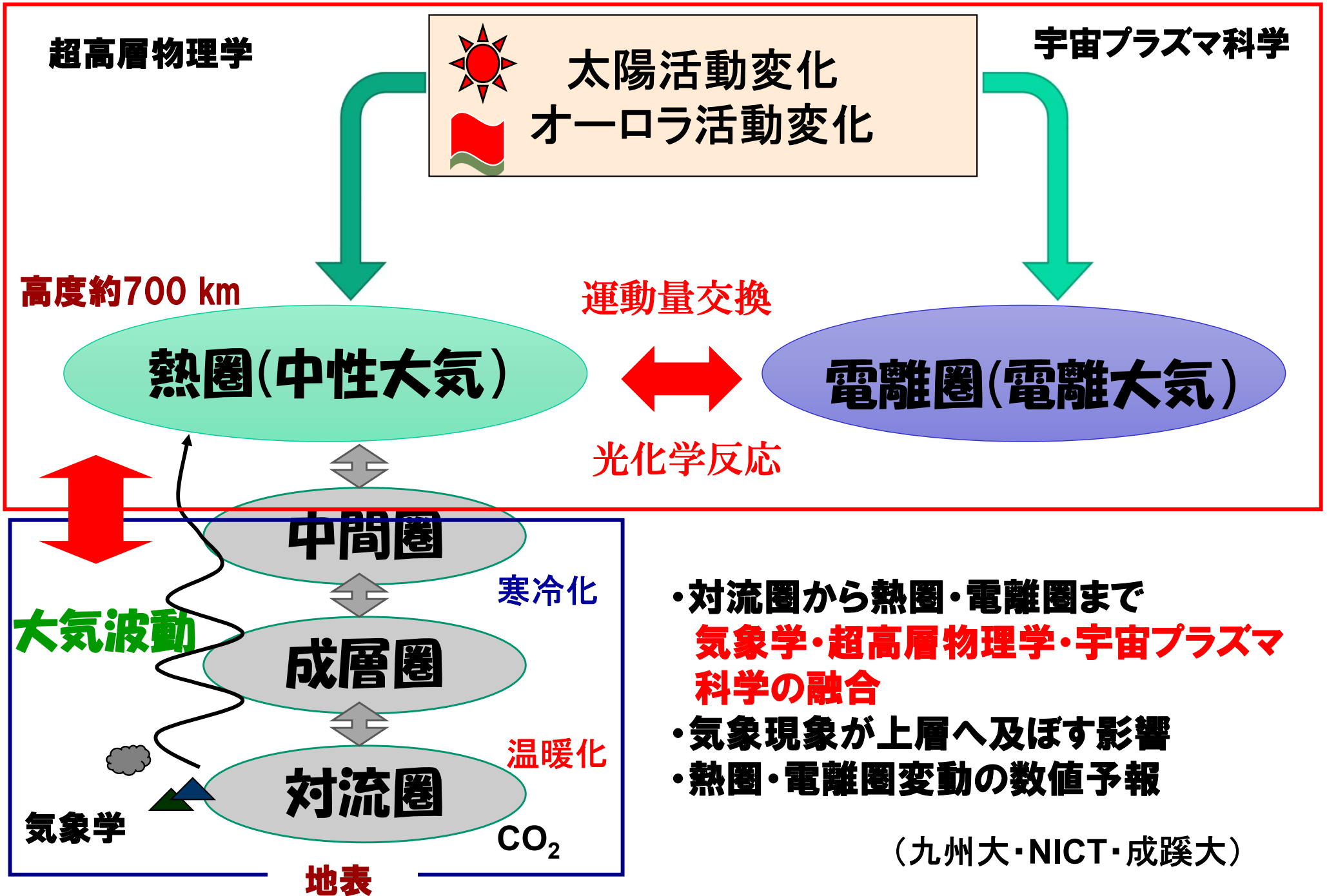
数値モデル（GAIA）の概要

①中性大気を記述する大気大循環モデル

・気象の数値予報モデルを鉛直上方（熱圏上端まで）に拡張

・**全球**をいくつかの格子点に分割し、各格子点上で、物理法則（運動方程式、連続の式、熱力学の式、放射伝達の方程式など）を解き、**大気全層における風速、密度、温度、大気組成**などの3次元分布を計算・予測

・下層大気の観測値（海面水温、氷床、対流圏循環の状態）および太陽活動度や磁気圏からのエネルギー降り込み量を基に、全大気の状態を物理的に計算
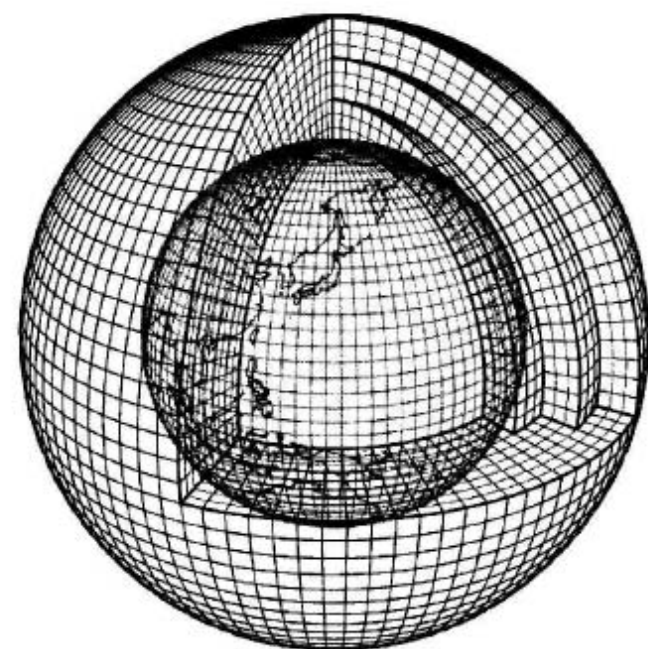
②電離大気を記述する電離圏モデル

③電気力学過程を記述するダイナモモデル

数値モデル（GAIA）の特徴

	数値モデル（GAIA model）	統計モデル（e.g. MSIS model）
長所	・数10分〜数時間・数日の大気変動を再現可能 ・局所的な大気構造を表現可能 ・現象の物理機構を調査可能 ・全球を均等にカバーするデータが得られる	・取り扱いが比較的簡単（PCで動作可能。様々なプログラムへの組み込みが可能） ・平均的な大気構造を容易に表現・理解できる
短所	・高時間・空間分解能にするほど高度な計算機資源（スーパーコンピュータ）が必要 ・物理・化学過程のモデル化に際し、仮定が必要 ・非線形方程式を数値的に解いていることから、何らかの観測との比較が必要(適用限界の把握が難しい)	・その時々の大気の状態をうまく表現できない ・局所的な大気構造を表現できない ・変動の時間変化をうまく表現できない

熱圏の局所構造は、下層大気の影響と考えられる。

→ 下層大気が上層に及ぼす影響はどのくらいか？

下層大気変動あり・なしの数値実験
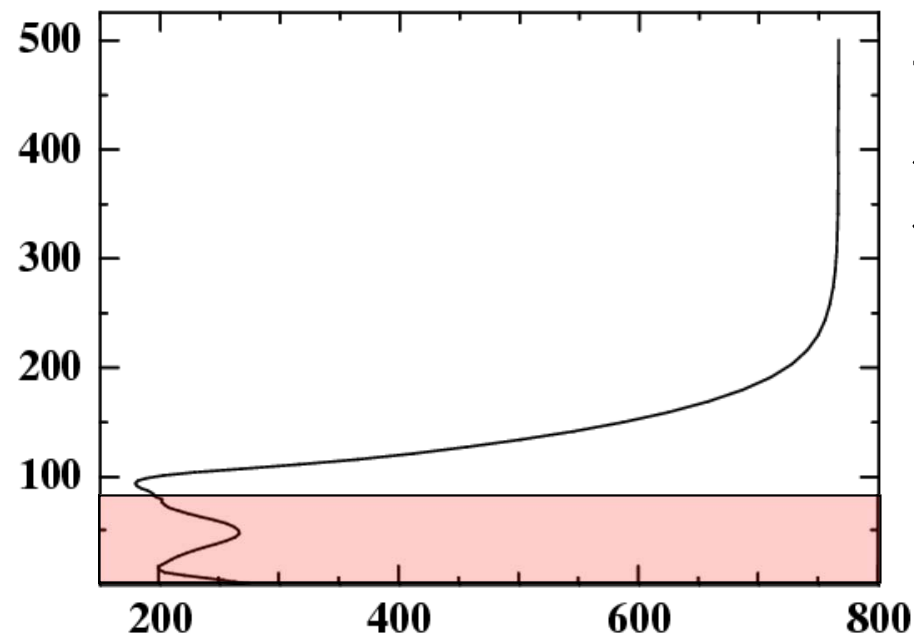
高度約80 km以下の
温度を全球一様とし、
風速をゼロとした計算

Results for usual calculations (about 306 km alt. UT=1)
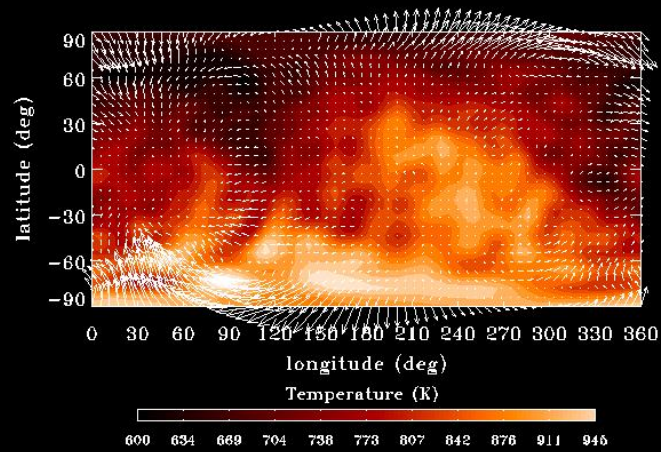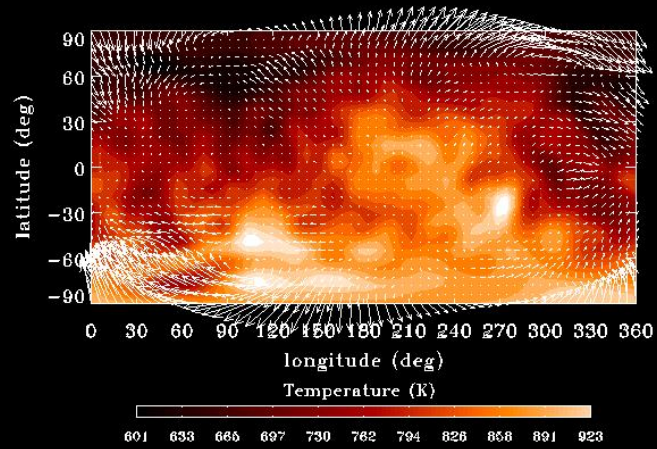
Suppression of effects from the lower atmosphere

After 1h

After 1day
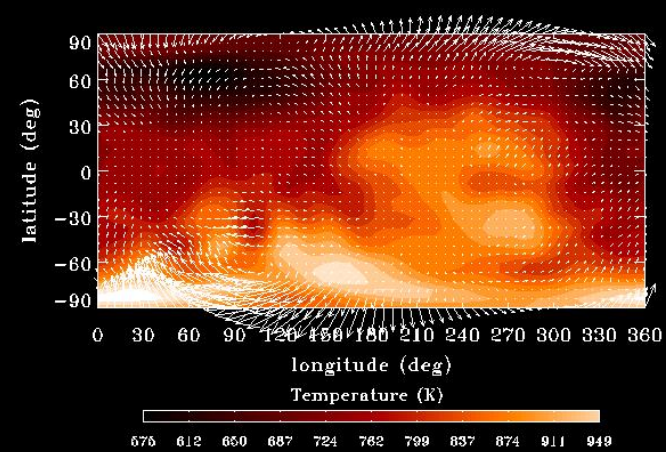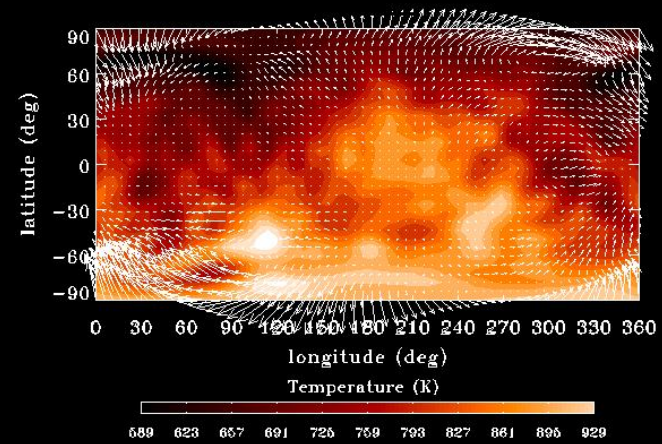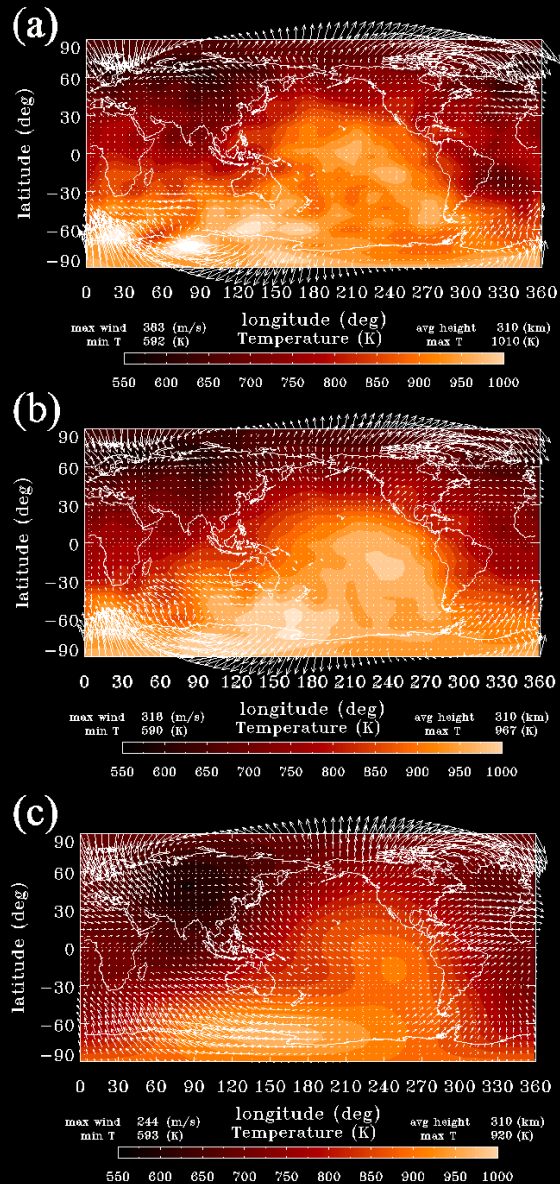
上から、
(a) 通常の計算
(b) 5日間の平均
(c) 経験モデル(NRLMSIS-00、HWM93)

The global distributions of temperature and horizontal wind obtained from (a) GCM calculations on a constant-pressure surface (~ 310 km altitude) at 01:00 UT on December 1, (b) 5-day average of GCM calculations at 01:00 UT, and (c) the NRLMSISE-00 and HWM-93 empirical models. Note that the strength of the maximum wind vector is different in each

O/N2のグローバル分布
~ 大気循環とTAD/TIDの指標として

Solar EUV & Aurorally-Driven Circulation and O-N₂ Composition
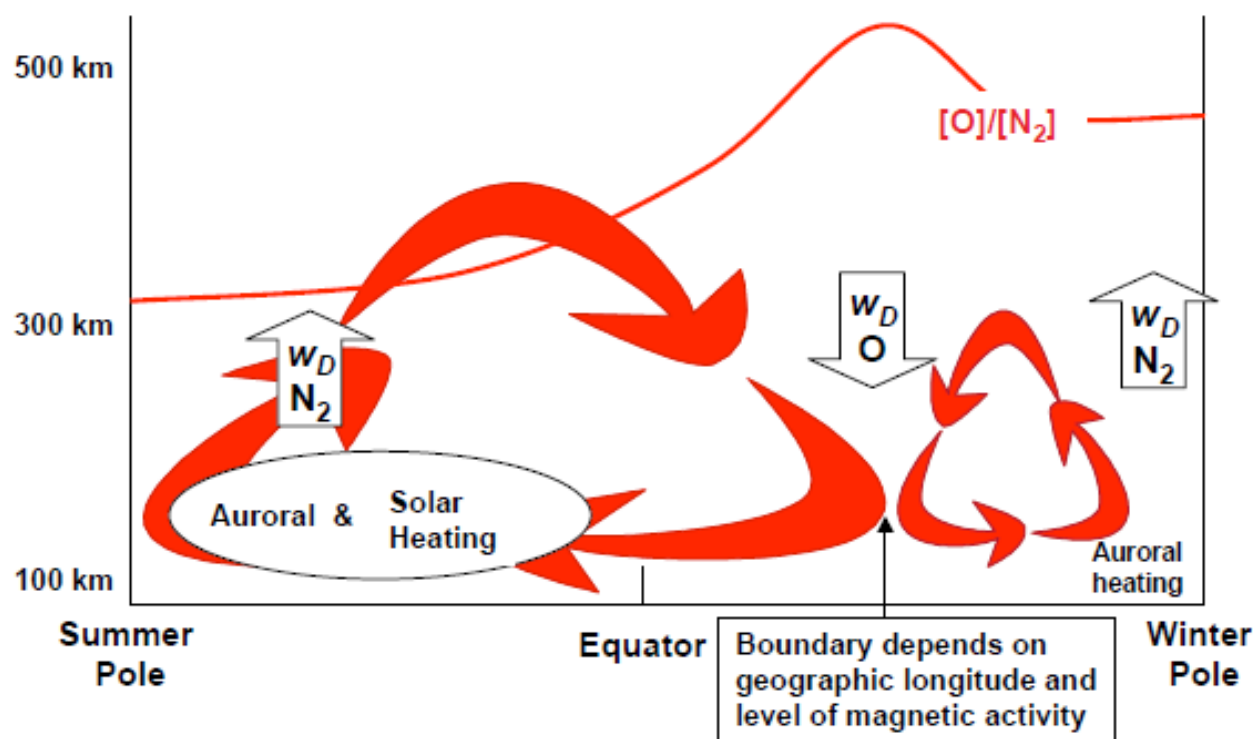
A secondary circulation cell exists in the winter hemisphere due to upwelling driven by aurora heating. The related O/N₂ variations play an important role in determining annual/semiannual variations of the thermosphere & ionosphere.

Forbes (2008)

O/N2の緯度、経度分布
日々変動、季節変動
太陽活動変化‥
の詳細を知りたい。

↓

・大気循環の変化が議論できる
・昼側電子密度が推定可能
・磁気嵐時の伝搬性擾乱の
　時空間変化がわかる

O/N2データとして、
AE衛星などに搭載された
質量分析器によるもの
がほとんどだった。
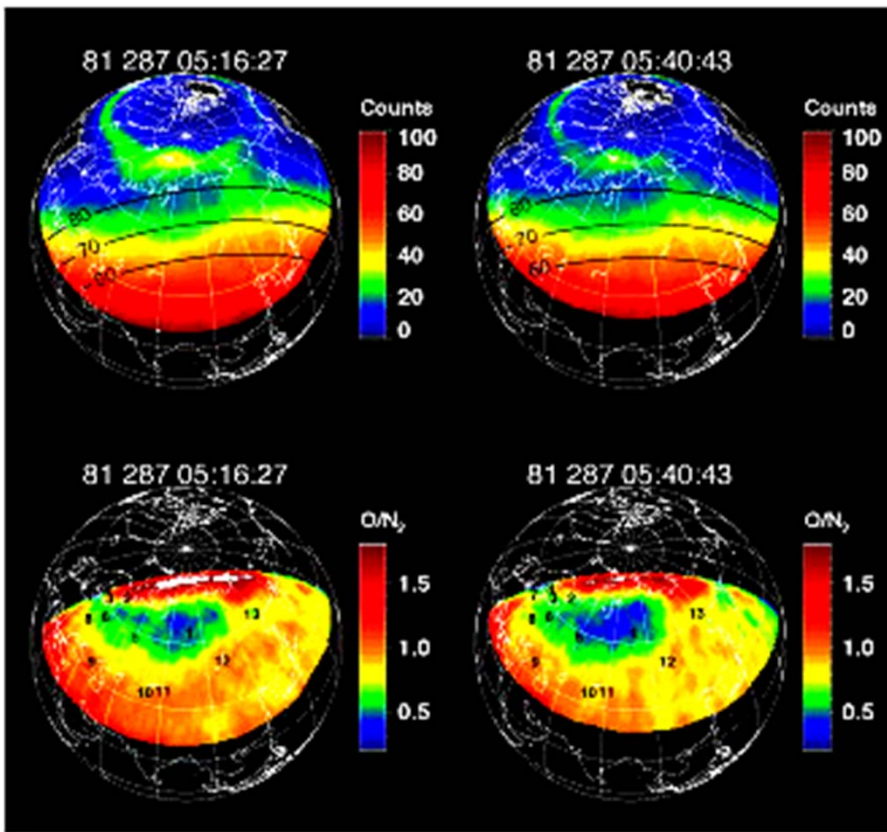
広範なO/N2分布を得る手段として、
紫外観測データを用いる方法が
Strickland et al.(1995)によって提案された。
DE1のFUV観測の例
上図がカウント値で、下図が
O/N2を導出したもの。

DE1で個々の事例が示された。

定常観測出来れば、データ同化に
利用可能？

GAIAによる計算例　11-12　LT

ρ (×10⁻¹⁰ kg/m³ F10.7=70; 200km)
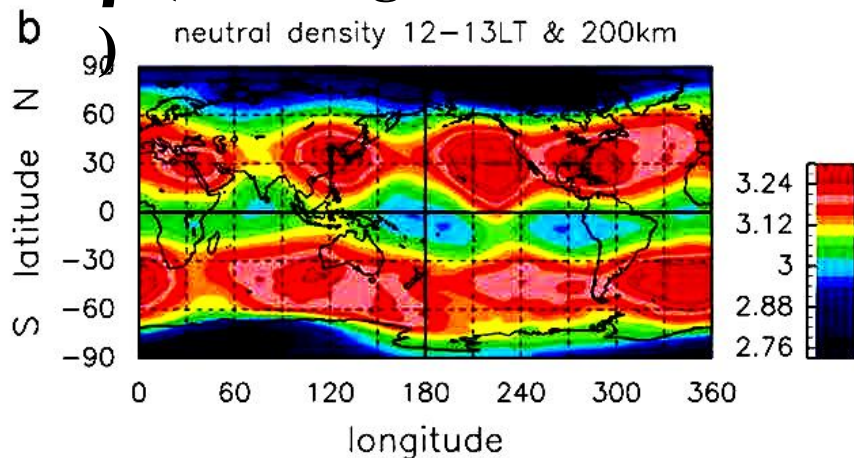
O/N2　(F10.7=70)
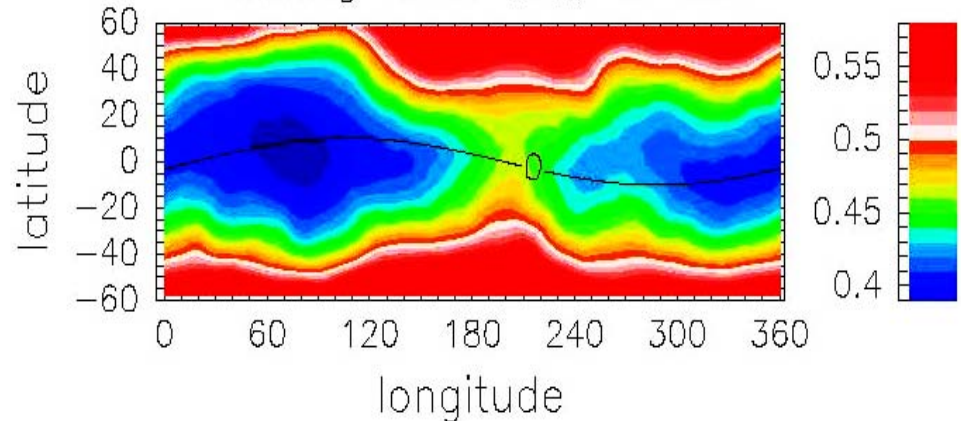
航空宇宙分野では、原子状酸素の情報が重要

原子状酸素によるポリイミド熱保護膜の劣化

10カ月間低軌道にあって1996年1月に回収された無人宇宙実験システム・SFUの電気推進実験表面に取り付けられたポリイミド熱保護膜の回収後の姿。

（写真提供：JAXA）

下部熱圏での酸素原子密度推定例
　　- 63μm放射、balloon platform at 37 km

Atomic Oxygen in the Lower Thermosphere

FLORENCE J. LIN, KELLY V. CHANCE, AND WESLEY A. TRAUB

Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts

We measured in thermal emission the 63-μm line due to thermospheric atomic oxygen O(^3P), using a far-infrared spectrometer on a balloon platform at 37 km altitude over Palestine, Texas (32°N), on June 20, 1983. From measurements of the equivalent width of this line at two elevation angles, we find a weak angular dependence: the equivalent width increases by a factor of 1.5 ± 0.3 as the angle decreases from +30° to +1°. Since the optical depth of the O(^3P) line is large, we cannot directly convert the measured line intensity to a column abundance. Instead, we interpret the measurements in terms of radiative transfer through a 16-layer atmosphere extending to 200 km. We use a model atmosphere for summer at 30°N, with an exospheric temperature of 1300 K, including (1) an assumed daytime atomic oxygen abundance profile constructed from recent chemical and dynamical models and (2) a water vapor abundance profile constructed from recent experimental and model results. For this assumed O(^3P) vertical profile shape we determine from our spectra at two elevation angles a multiplicative scaling factor of 0.8, with an altitude-dependent uncertainty. In the best-determined layer the uncertainty in the multiplier is ±0.2 at 119 km. The model-dependent peak atomic oxygen density is 3.6 (±1.9) × 10^{11} cm^{-3} at an altitude of about 101 km.

A global measurement of lower thermosphere atomic oxygen densities

K. U. Grossmann, M. Kaufmann, and E. Gerstner

Department of Physics, University of Wuppertal, Wuppertal, Germany

1994，1997にスペースシャトルから放出

140 km
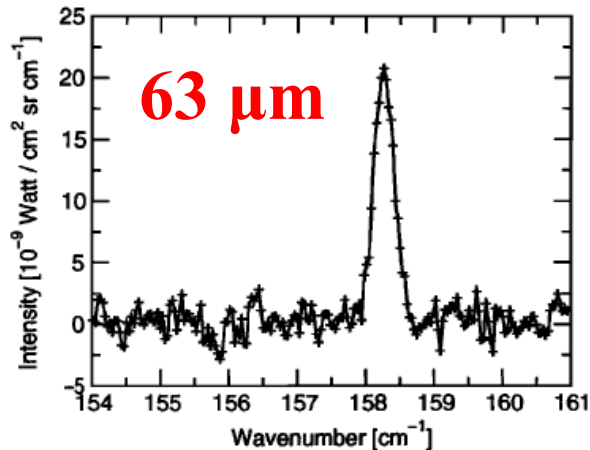
Figure 1. Single spectrum of the O(^{3}P) emission line at 63 µm recorded by CRISTA-2 at an altitude of 151 km.
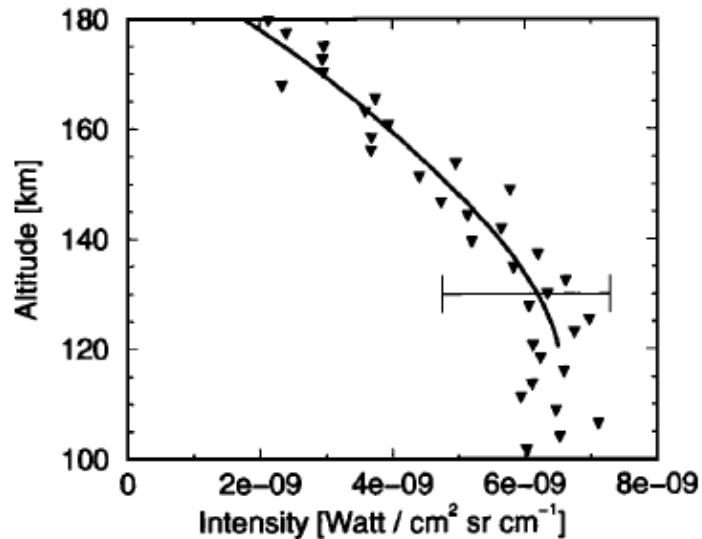
Figure 2. Line integrated limb radiance profile (CRISTA-2, one altitude scan). For details see text.
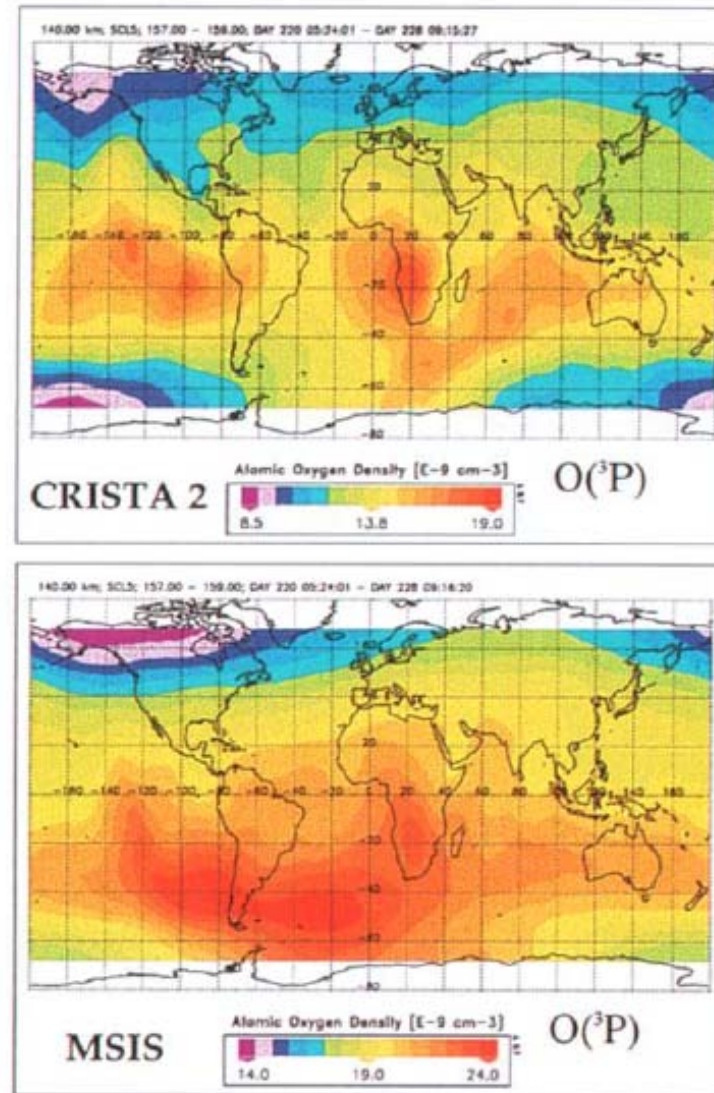
Plate 1. Atomic oxygen concentrations at 140 km measured by CRISTA-2 August 13 – 15, 1997 (upper panel). The color scale is 8.5 – 19.0 · 10^9 cm^{-1} in increments of 0.7 · 10^9 cm^{-3}. MSIS model atomic oxygen concentrations (lower panel) calculated for the conditions of the experimental data. The color scale here is 14.0 – 24.0 · 10^9 cm^{-3} in increments of 0.7 · 10^9 cm^{-3}.

Ionosphere-Thermosphere Validation Matrix

|	Tn	U	V	O_2	N_2	O	NO	N	$n_n(\rho)$	n_e	O^+	NO^+	O_2^+	T_e	T_i	u_i	v_i
ISRs	x^1	x^1	x^1							x				x	x	x	x
Digisondes										x						x	x
SuperDarn																x	x
Imagers					x^2	x^2				x^2							
Accelerometers[‡]									x								
Satellite Drag[‡]									x								
DE 2[‡]	x	x	x	x	x	x		x	x	x	x			x	x	x	x
AE[‡]				x	x	x	x	x	x	x	x	x	x	x	x		
GPS systems										x							
DMSP/NOAA										x				x	x	x^3	x^3
TIMED	x	x	x		x	x	x										
SNOE							x										
Ground FPI	x	x	x														
GroundImager																	
ArchivedRocket[†]		*x*	*x*	*x*		*x*	*x*		*x*	*x*							
CHAMP		x							X								
SWARM									x							x	
GAIA	x	x	x	x	x	x			x	x	x	△	△	△	△	x	x

(from Psnuux&uwjxjsyfyts%r fyjwfqx)

[1] Below ~130 km

[2] O/N_2 during the day, electron densities at night, also coupling parameters. Useful composition data could not be obtained from POLAR and IMAGE

[‡] In situ or mainly in situ measurements, DE 2 and AE were multi-instrumented missions

[†] Only some of these variables were available on any particular rocket flight. Generally sporadic.

[3] Derived quantities with assumptions

最近の話題より

2022年2月のスターリンク衛星の落下事故
https://www.nytimes.com/2022/02/09/science/spacex-satellites-storm.html

Solar Storm Destroys 40 New SpaceX Satellites in Orbit

The geomagnetic incident resulted in the Starlink transmitters drifting back into Earth's atmosphere, where they will burn up, potentially costing the company about $100 million.
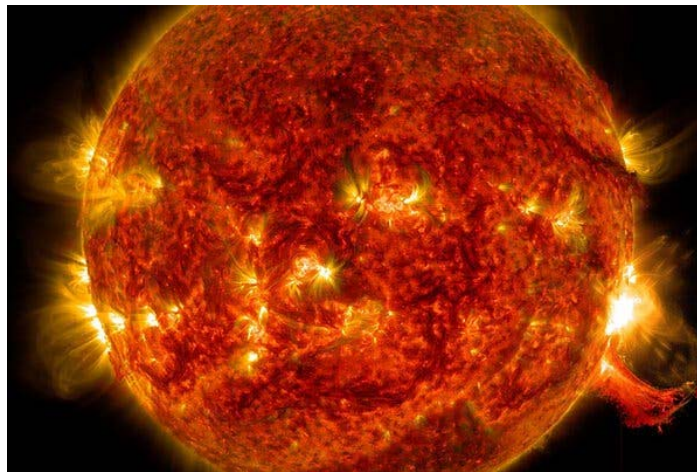
A geomagnetic storm triggered by a recent outburst of the sun knocked out up to 40 of 49 newly launched Starlink satellites.Credit...GSFC/NASA

https://www.express.co.uk/news/science/1278064/Starlink-satellites-how-many-Starlink-satellites-has-SpaceX-launched
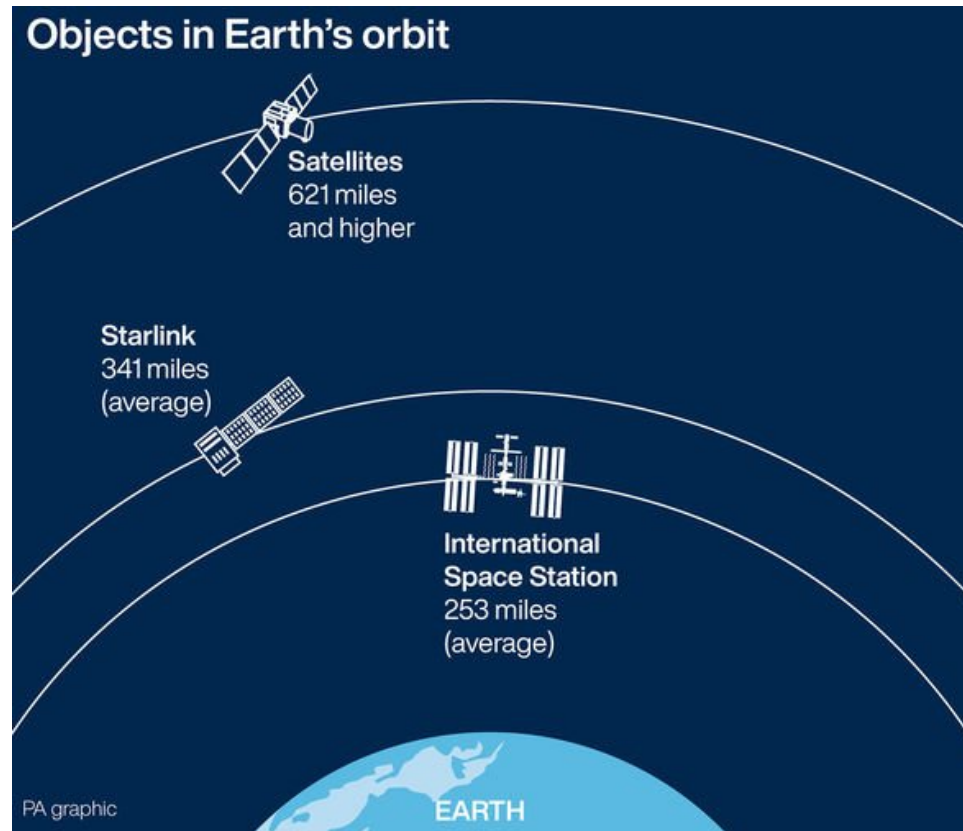
Double minor geomagnetic storms heated the thermosphere.
Enhancements (>50 %) of the thermospheric mass density at 200 km caused a strong drag force to the starlink satellites.

Derivation of the thermospheric density from the satellite motion

Simplified theory

Air drag force

$$F_D = \frac{1}{2} \rho C_D (V_s - U)^2 A_r$$

ρ：atmospheric density
C_D: drag coefficient (~2.2)
V_s: velocity of the satellite
U: wind velocity
A_r: satellite cross-section

Energy of the artificial satellite (assuming circular motion)

$$E = \frac{1}{2} m V_s^2 - \frac{GMm}{r}$$

m：mass of the satellite
G: universal gravitational constant
M: mass of the Earth
m: mass of the satellite
r: distance between the center of the Earth and the satellite

From a balance between gravitational and centrifugal forces, E can be written as

$$E = -\frac{GMm}{2r}$$

Energy reduction rate caused by the air drag force

$$\frac{dE}{dt} = -F_D (V_s - U) = -\frac{1}{2} \rho C_D (V_s - U)^3 A_r$$

We assume V = Vs-U~ Vs.

$$\frac{dE}{dt} = \frac{GMm}{2r^2}\frac{dr}{dt} = -\frac{1}{2}\rho C_D V^3 A_r$$

$$V = \sqrt{\frac{GM}{r}}$$

The rate of orbital decay or the atmospheric density is written as follows,

$$\frac{dr}{dt} = -\frac{\rho V C_D A_r r}{m} \quad \Longleftrightarrow \quad \rho = -\frac{m}{V C_D A_r r}\frac{dr}{dt}$$

Changes in the orbital period was used for estimation of the averaged atmospheric density in earlier times.

$$\dot{T} = \frac{dT}{dt} = -\frac{3\pi C_D A_r r}{m}\rho$$

$$\left(T = \frac{2\pi r}{V} \right)$$
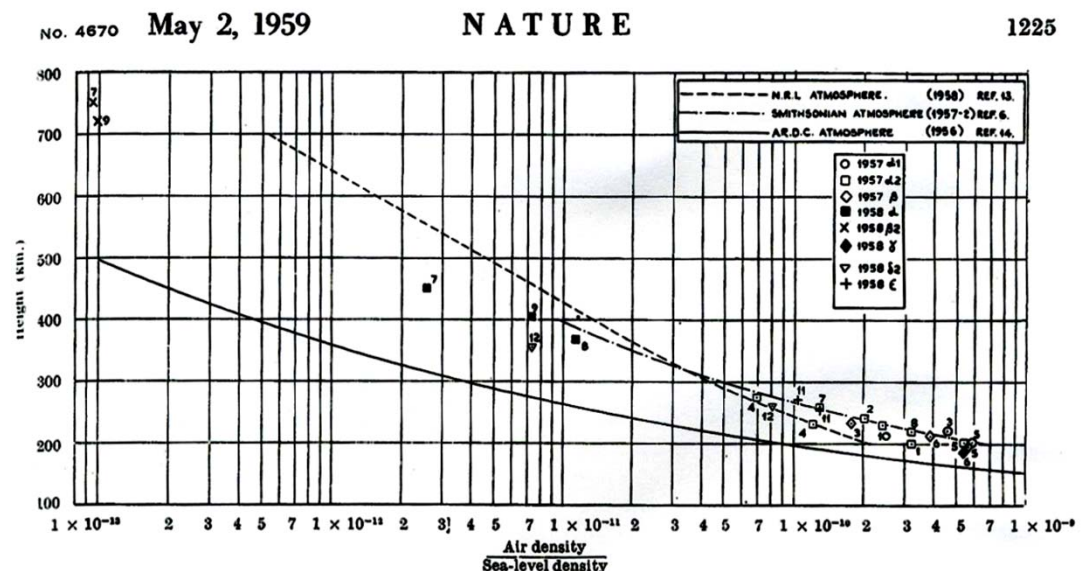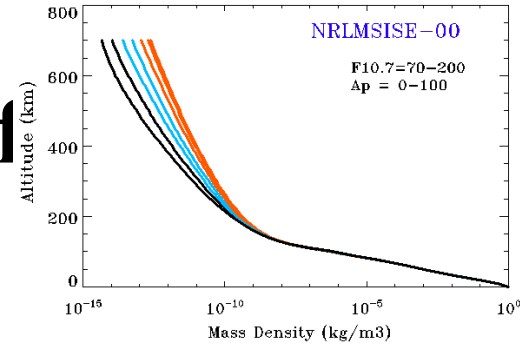
King-Hele [1959]

Fig. 1. Values of air density obtained by means of satellites (refs. 1–12), with proposed 'standard atmospheres' (refs. 6, 13, 14). Reference numbers are shown beside the plotted points
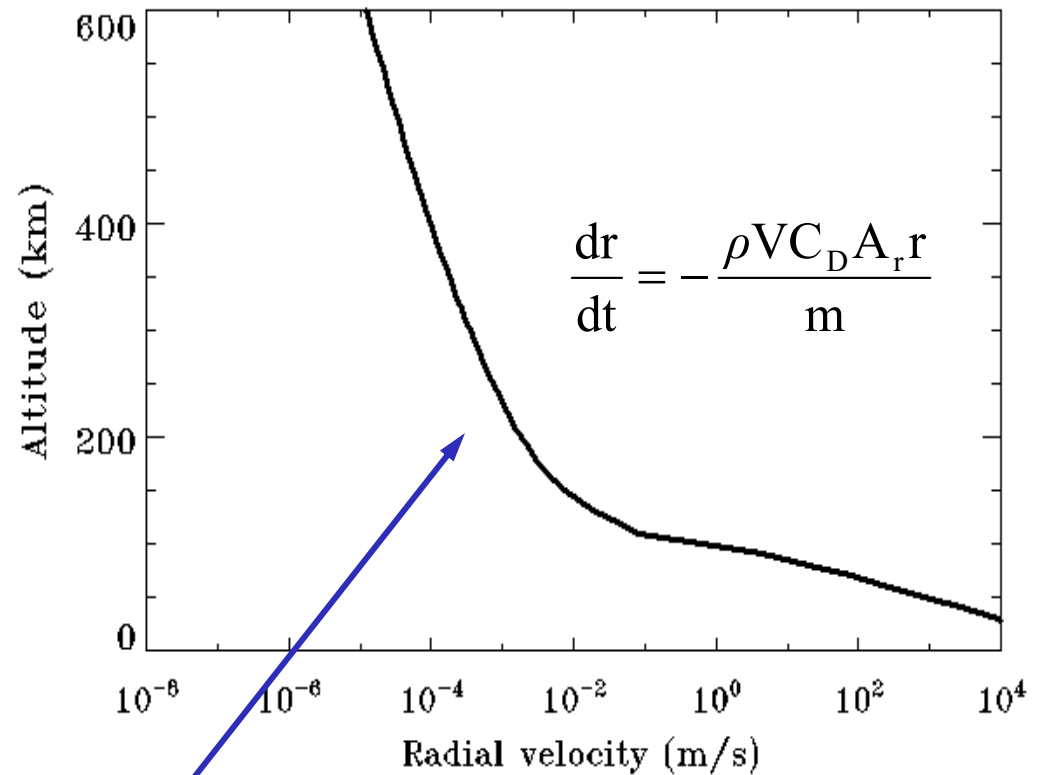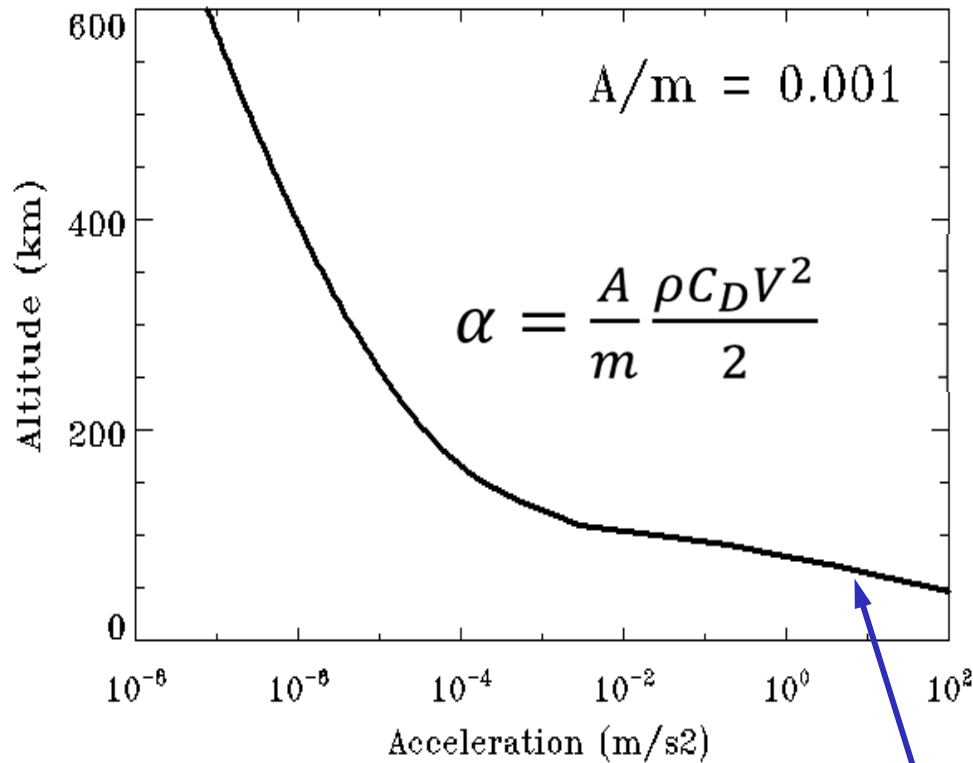
Example of calculations: f... ellite

NRLMSISE-00
F10.7=70-200
Ap = 0-100

Acceleration of satellite due to air drag force

infall velocity (rate of fall) of satellite due to air drag force

$$\alpha = \frac{A}{m}\frac{\rho C_D V^2}{2}$$

A/m = 0.001

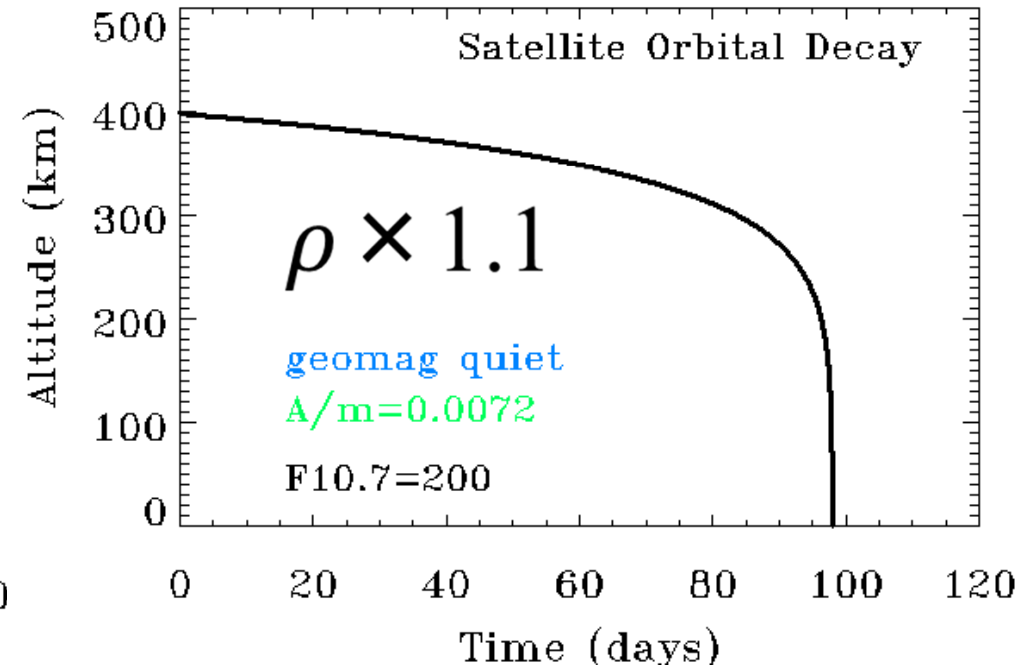$$\frac{dr}{dt} = -\frac{\rho V C_D A_r r}{m}$$

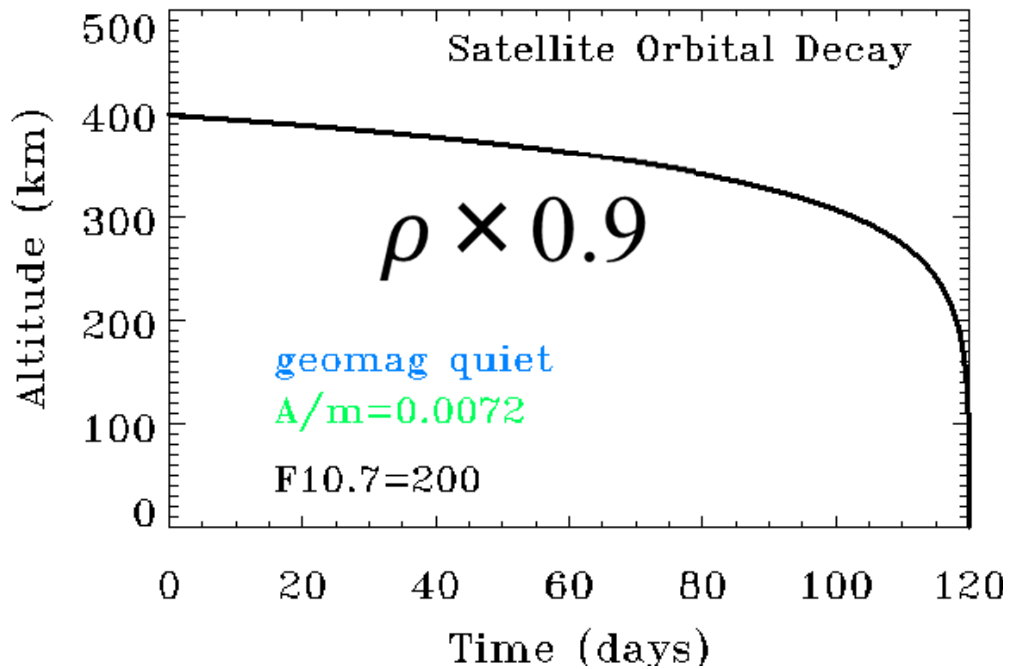**Shapes of the curve are strongly dependent on the thermospheric mass density.**

Satellite mass (kg): 86
Satellite area (m^2) : 0.62
Starting height (km) 400
Solar Radio Flux (F10.7 index): 200
Geomagnetic activity (Ap): 5 (quiet)

TAIYO satellite (Kato et al., 1979)
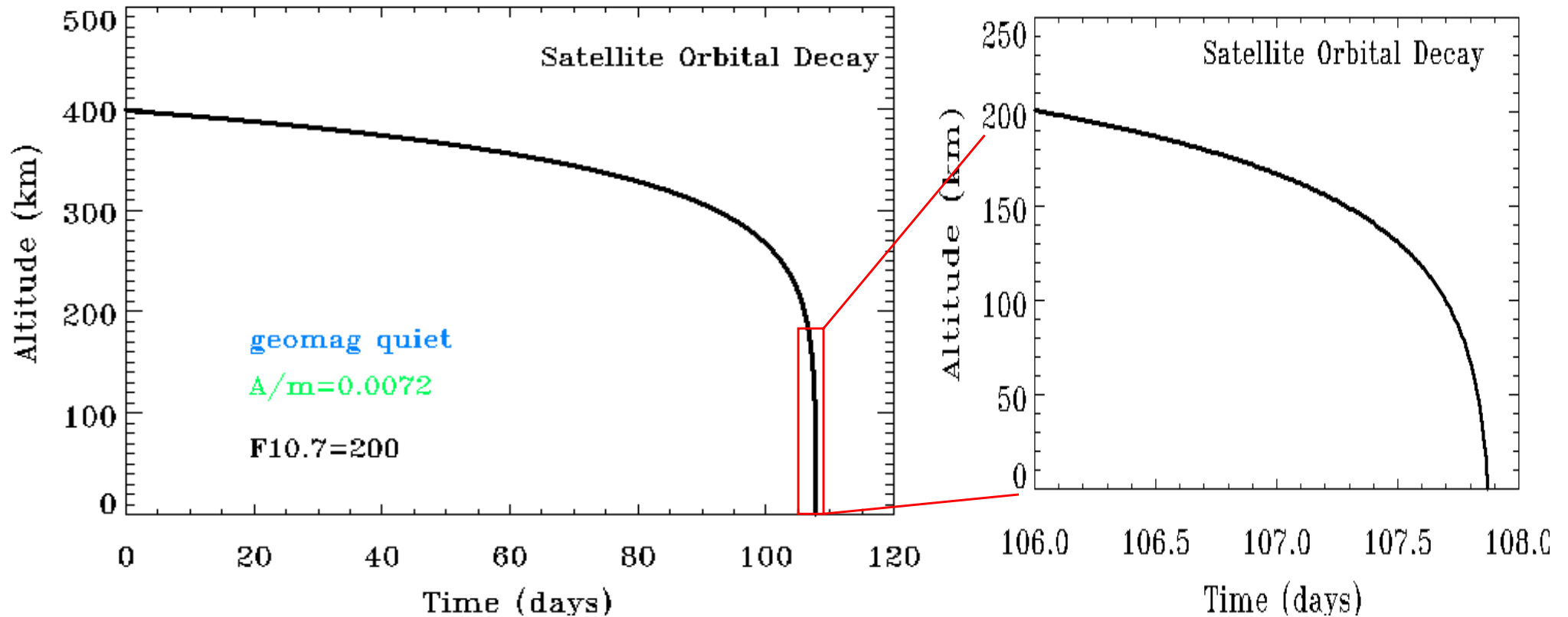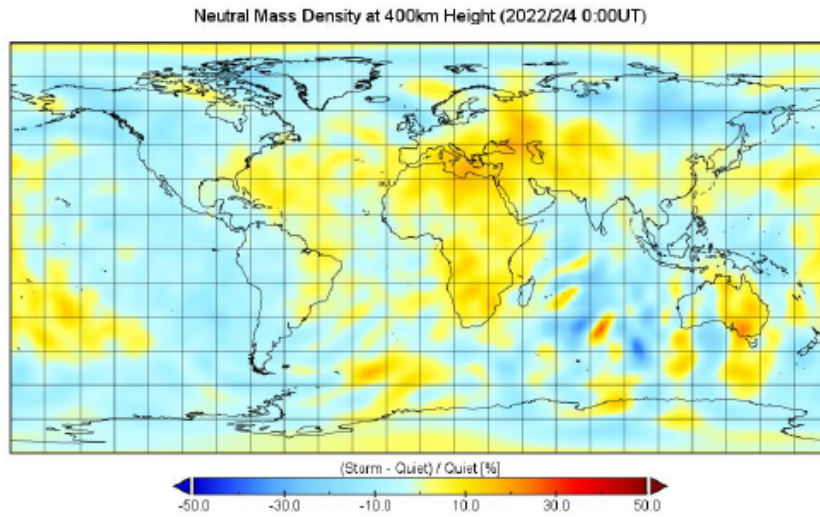

Lifetime of satellite at 200 km is 1～2 days.

These simple calculations suggest that prediction
of lifetime of the LEO satellite is quite difficult.

Kataoka et al. (Journal of Space Weather and Space Climate, 2022)

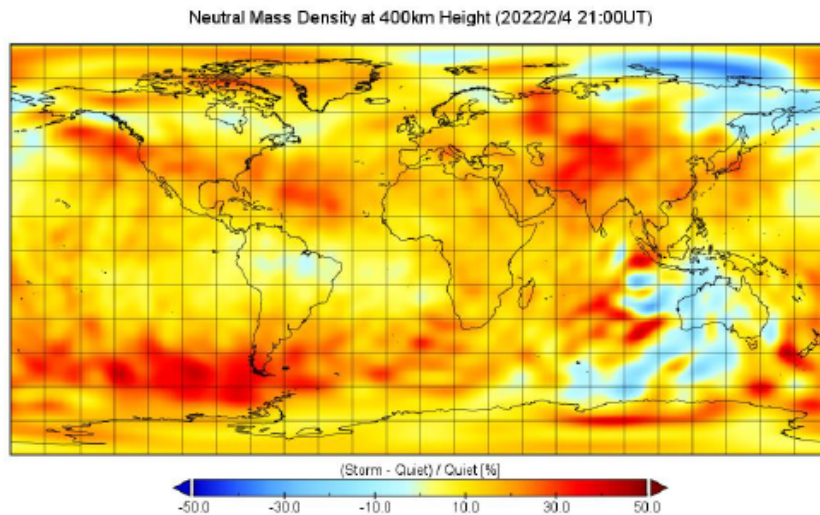## Unexpected space weather causing the reentry of 38 Starlink satellites in February 2022

400 km

Feb 4

00:00 UT

Neutral Mass Density at 400km Height (2022/2/4 0:00UT)

(Storm - Quiet) / Quiet [%]
-50.0   -30.0   -10.0   10.0   30.0   50.0

Thermospheric mass density variations at about **400 km** during geomagnetically quiet (upper panel) and disturbed (lower panel) periods simulated with GAIA.

Kataoka et al. (2022)

400 km

Feb 4

21:00 UT

Neutral Mass Density at 400km Height (2022/2/4 21:00UT)

(Storm - Quiet) / Quiet [%]
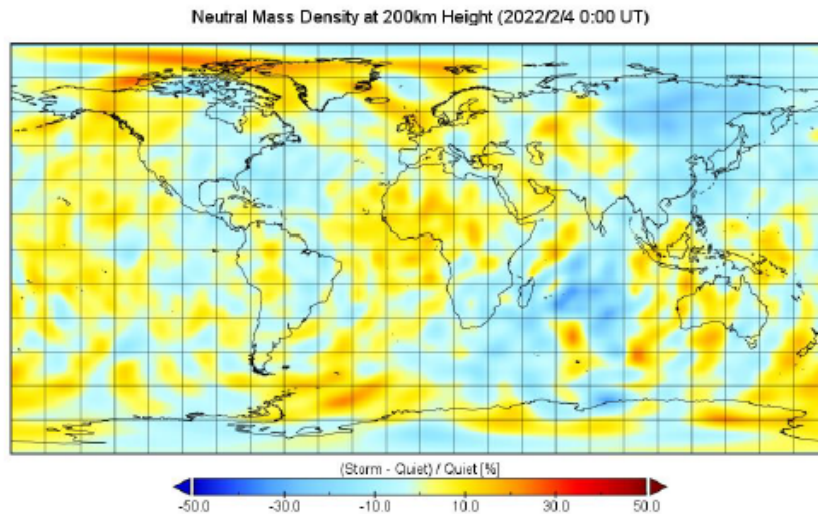-50.0   -30.0   -10.0   10.0   30.0   50.0

GAIA simulations presented by NICT

R rsnxyw~ɫkNɟyjwsfɕꟷFkkfnwꬷfsi%
Htr r zsꟷhfyɫtsxꬷr fyjwfɋxꬷrsꟷfufsjxj.
https://www.soumu.go.jp/main_content/000794766.pdf

Figure 6. Simulation results of the thermospheric mass density at 400 km altitude, (storm-quiet)/quiet

Kataoka et al. (2022)

200 km
Feb 4
00:00 UT

Neutral Mass Density at 200km Height (2022/2/4 0:00 UT)

(Storm - Quiet) / Quiet [%]
-50.0   -30.0   -10.0   10.0   30.0   50.0

Thermospheric mass density variations at about **200 km** during geomagnetically quiet (upper panel) and disturbed (lower panel) periods simulated with GAIA.

200 km
Feb 4
00:00 UT

Neutral Mass Density at 200km Height (2022/2/4 21:00 UT)

(Storm - Quiet) / Quiet [%]
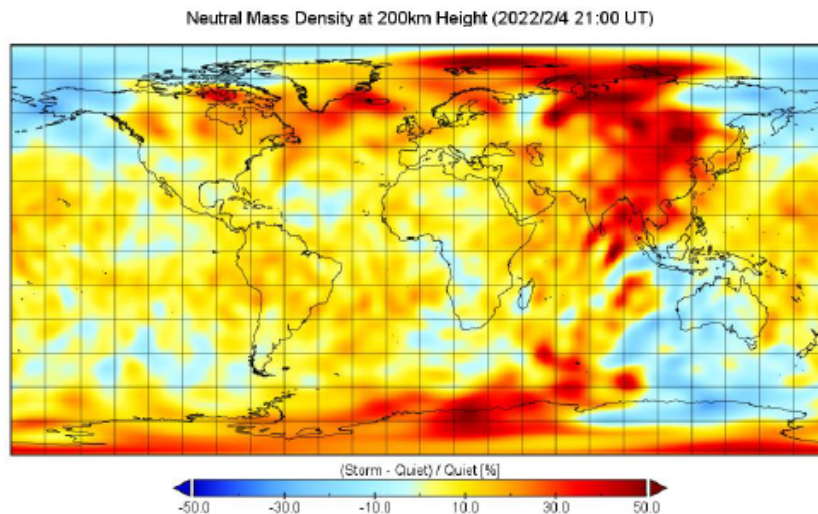-50.0   -30.0   -10.0   10.0   30.0   50.0

Figure 7. Simulation results of the thermospheric mass density at 200 km altitude, (storm-quiet)/quiet in %, for 0000 UT and 2100 UT on February 4, 2022. The selected quiet day is February 1, 2022.

Simulation results suggest that the wave-like patterns are superimposed on the mass density enhancements (> 50 %), which was likely caused by horizontal expansion of the heated air. Therefore, the actual thermospheric disturbances at around 200 km altitude might occur with larger amplitude in the wider area than those we thought in some cases.

SGEPSS将来構想
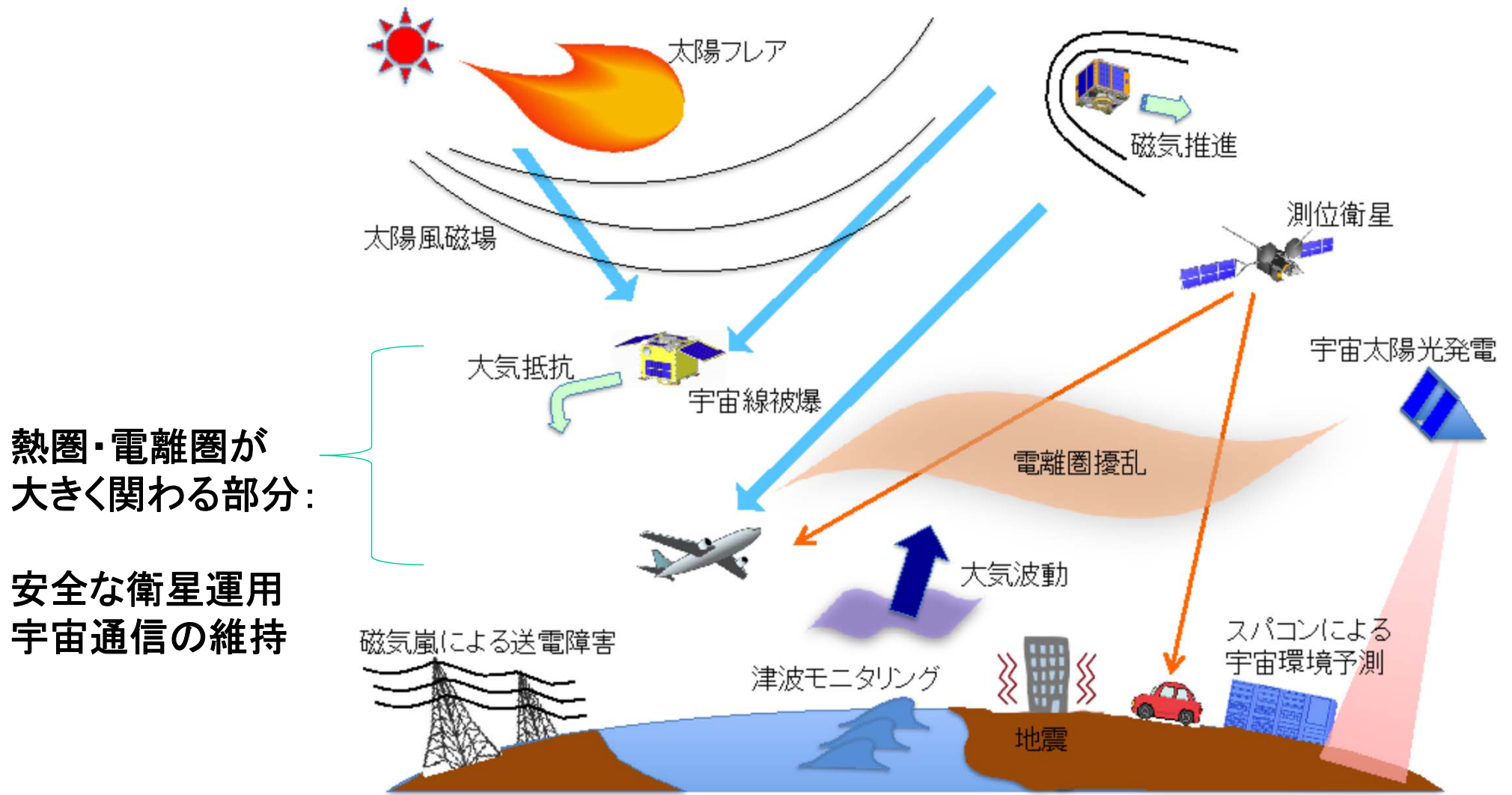http://www.sgepss.org/sgepss/shorai/SGEPSS_syorai_digest_Jan2013.pdf

図 3.1 太陽地球圏と人間活動とのかかわり

まとめ

地上(レーダー、光学観測)・衛星観測、全球モデルの
進展により、磁気嵐時の熱圏変動や、下層大気起源の
熱圏変動が明らかになってきた。

特に、近年のCHAMPによる、熱圏大気質量密度計測
は大きな進展であった。ただし、大気組成の時空間変動
に関しては十分なデータがない。

さらに、高度150-250kmでの熱圏変動はよくは理解され
ていない（Space-Xの衛星事故はその表れ）。

今後の研究の方向性：ドラッグデータや、ありとあらゆるデータ
を使って、データ同化→予報研究、または機械学習による予報
が進展するかもしれない。