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The mesosphere & thermosphere

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- *Edmund Henley (Met Office)*
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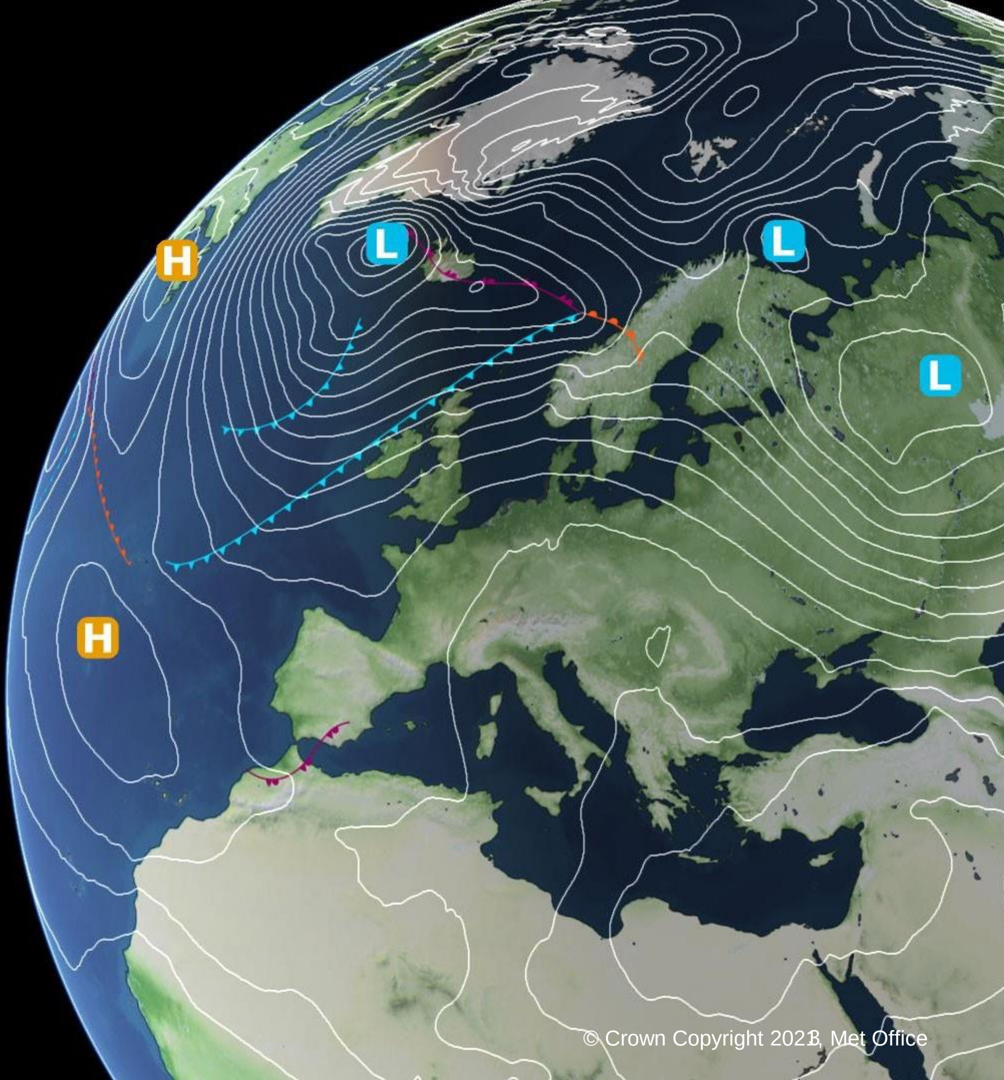
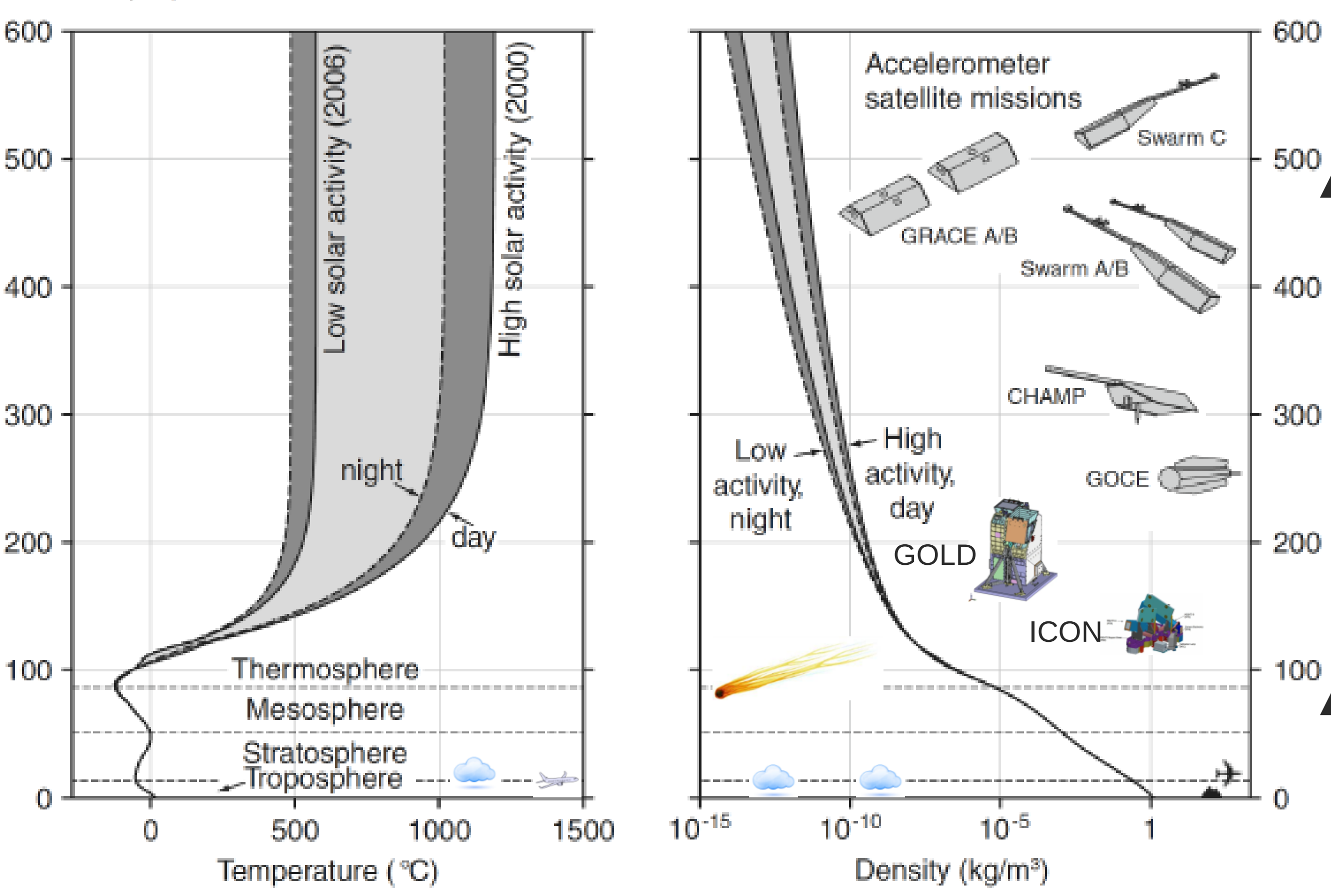
STFC Introductory Course in Solar & Solar-terrestrial Physics
University of Sheffield, 4 September 2024



Structure of lecture

1. Thermal structure: energy sources and sinks
2. Dynamics: wind structure, momentum balance and waves
3. Observations and modelling

The "Ignorosphere": ~100-300 km altitude



Neutral atmosphere: remote sensing hard

In situ measurements possible with low-altitude satellites above

Gap! Only a few remote sensing satellites (GOLD, ICON),

Sounding rockets (~120 km), radar (~100 km) & weather balloons (<30 km) and satellites (< 100 km) can measure below

Height dependence of atmospheric temperature and density according to the NRLMSISE-00 model (Doornbos, 2011)

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INVESTING IN SPACE

SpaceX to lose as many as 40 Starlink satellites due to space storm

PUBLISHED WED, FEB 9 2022·10:53 AM EST | UPDATED WED, FEB 9 2022·6:42 PM EST

Michael Sheetz
@THESHEETZTWEETZ

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KEY POINTS

- Elon Musk's SpaceX expects to lose nearly an entire launch's worth of Starlink satellites after a storm created by the sun struck the Earth's atmosphere.
- The company launched 49 Starlink satellites on Feb. 3, but "up to 40 of the satellites" will be lost due to this geomagnetic storm.
- SpaceX does not disclose the exact cost of its Starlink satellites or its Falcon 9 launches – but losing the majority of the mission could be a financial hit upward of $50 million, based on previous statements from company leadership.

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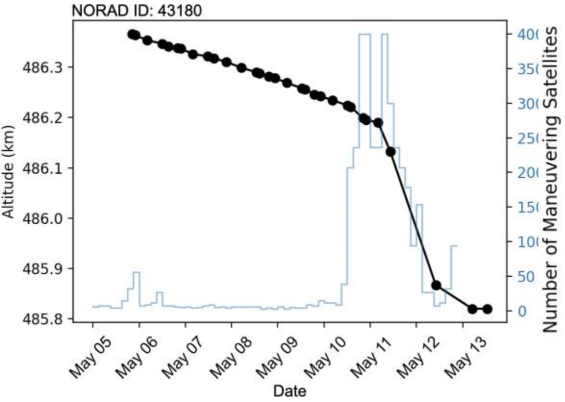
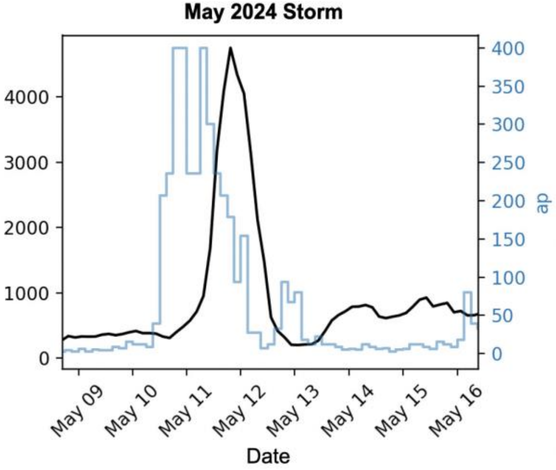
Impact of May 2024 Geomagnetic Storm





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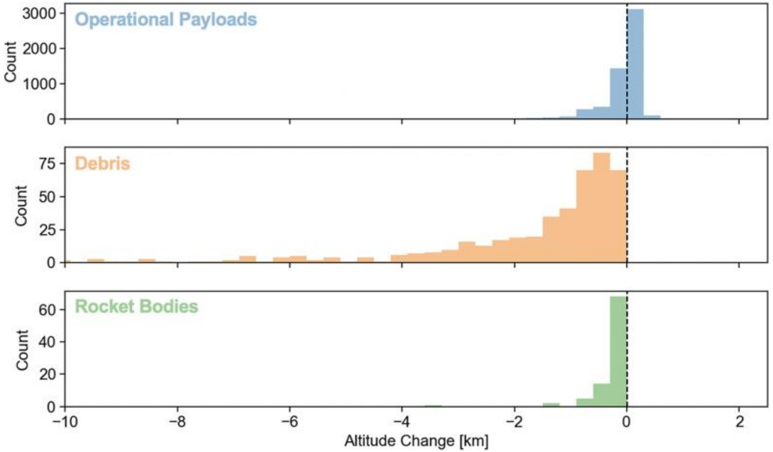

- Decrease in SATCAT-43180 changed from 38 m/day before storm to 180 m/day
- En-masse (mainly Starlink) manoeuvres to correct altitude changes
- Change in altitude at 400-700 km thus reduced for satellite but not debris

Parker and Linares (2024) https://doi.org/10.2514/1.A36164

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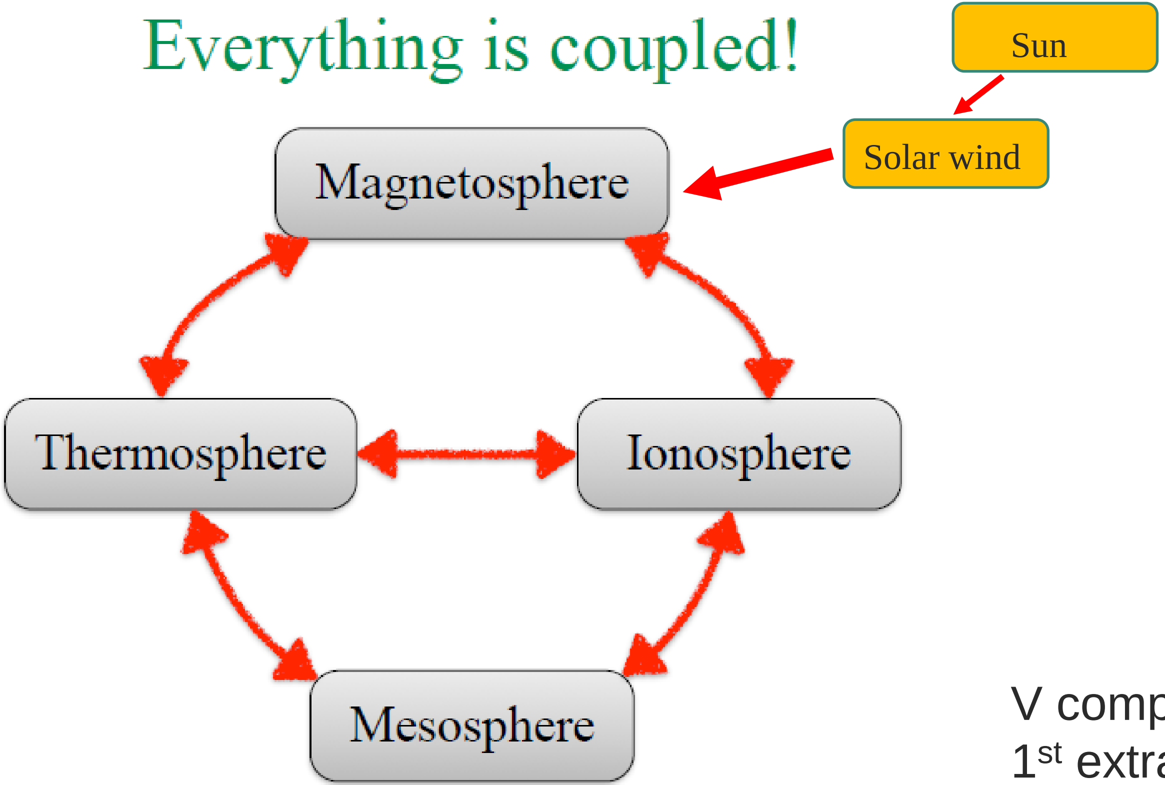
Everything is coupled!



V complex – see 1st extra slide for more detail

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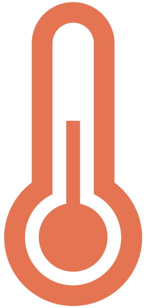
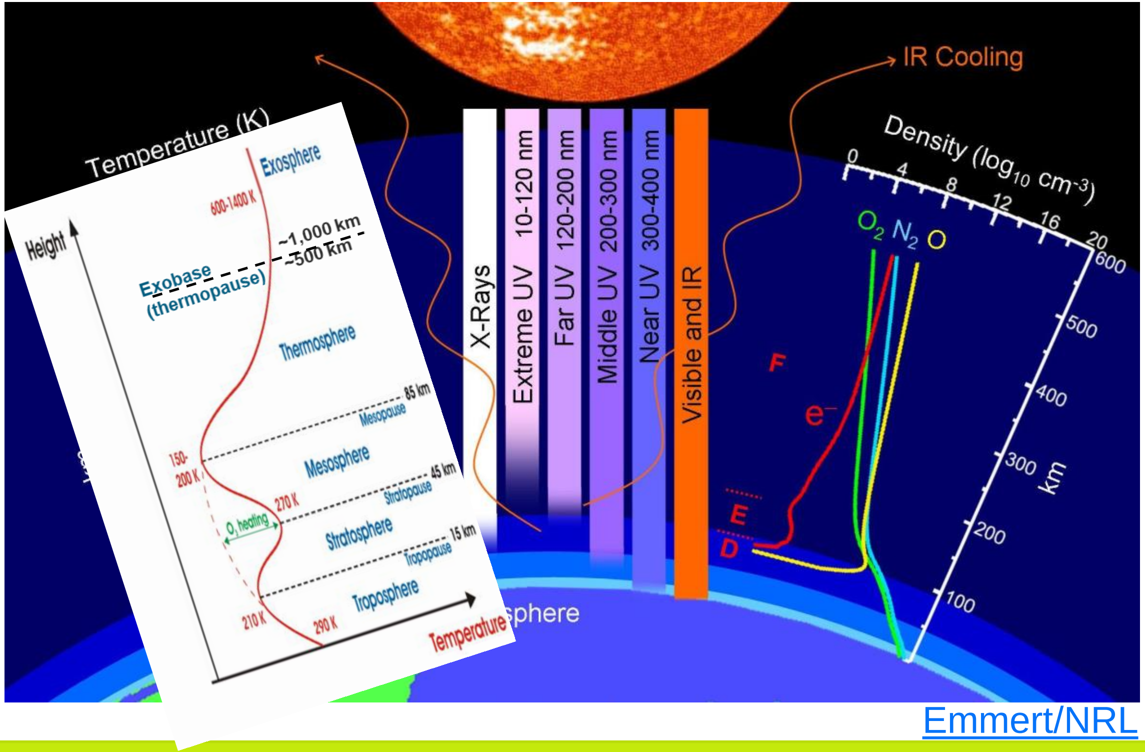
Part 1: Thermal structure, energetics



Spheres & pauses: temperature

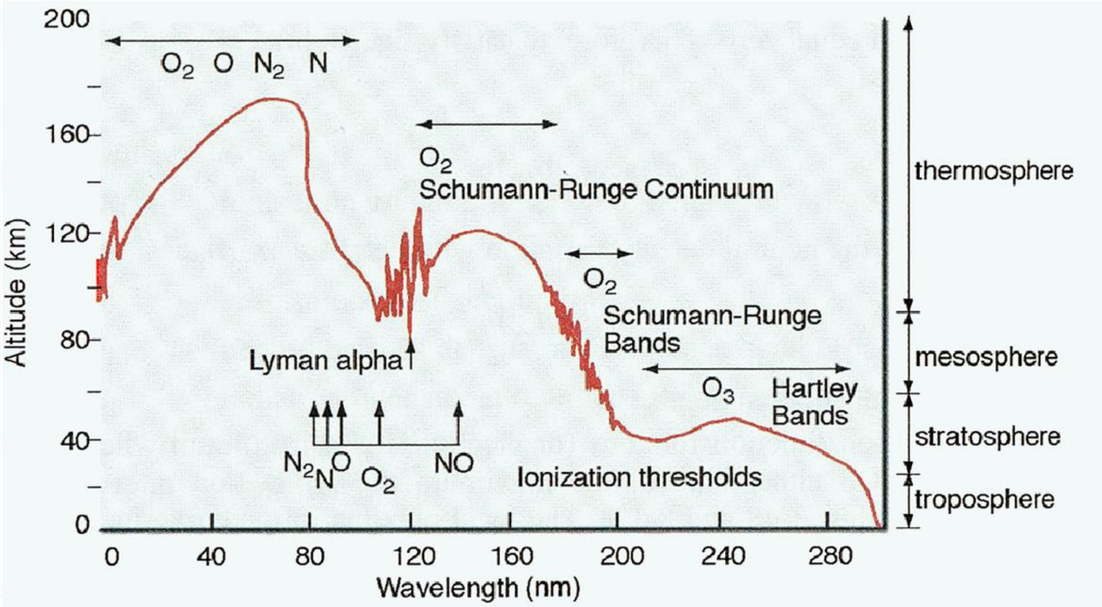


Emmert/NRL

- Gradients arise due to heating and cooling processes
- Radiation a key process
- Different wavelengths involved at different heights
- Spheres' composition a key factor in radiation budget → temperature profile

Solar radiation absorption

Wavelength	*Atmospheric absorbers*
121.6 nm	Solar Lyman α line, absorbed by O_2 in mesosphere; no absorption by O_3
100-175 nm	O_2 Schumann Runge continuum. Absorption by O_2 in thermosphere.
175-200 nm	O_2 Schumann Runge bands. Absorption by O_2 in mesosphere & upper stratosphere.
200-242 nm	O_2 Herzberg continuum. Absorption by O_2 in stratosphere & weakly in mesosphere



Middle atmosphere radiative heating

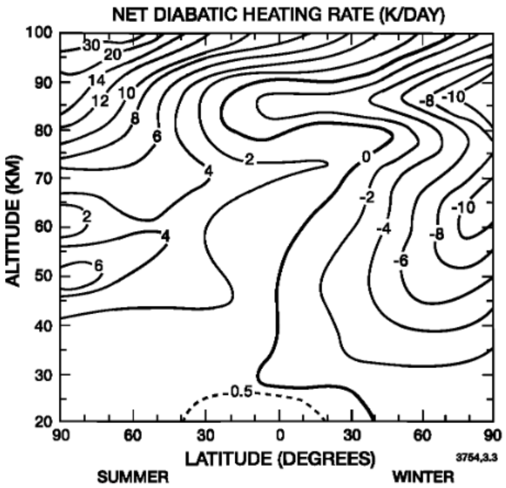
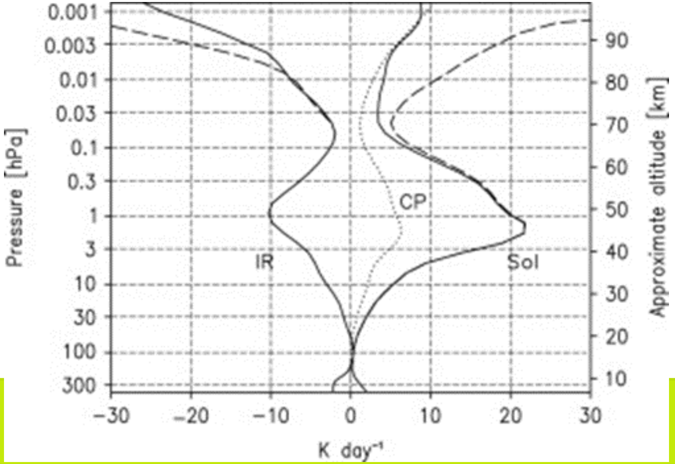
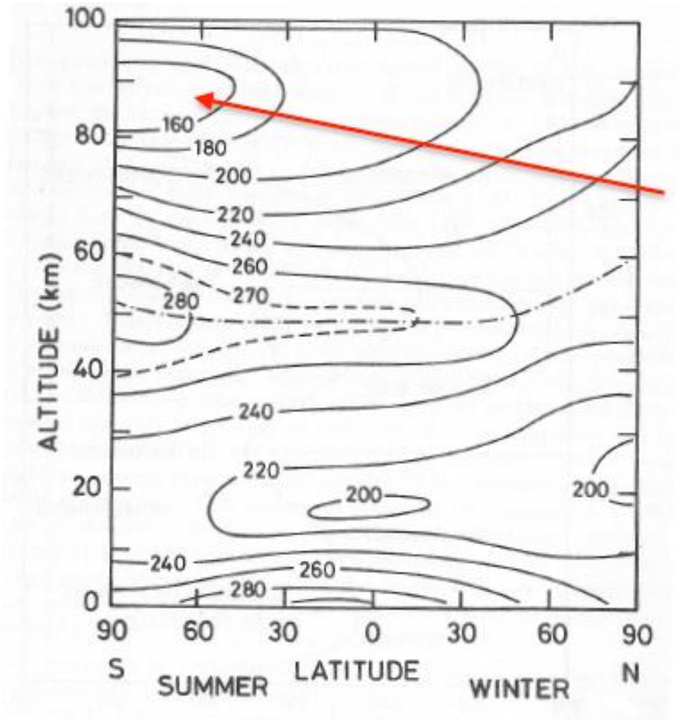


Figure 3.3. Net radiative heating rate associated with (1) absorption of ultraviolet radiation by molecular oxygen in the upper mesosphere and thermosphere, and by ozone in the stratosphere and mesosphere, and (2) emission of infrared radiation by atmospheric CO_2, O_3, and H_2O. Values given in K/day and positive in the summer hemisphere (net diabatic heating) and
405224118621723612012901211717621604910 4 phere. From London (1980).

- O3 heating maximises near 50 km – this creates the stratopause
- IR cooling (mainly due to CO2) leads to net heating (cooling) in summer (winter)
- So highest (lowest) temperatures in extratropical summer (winter) stratosphere and mesosphere, right?



Middle atmosphere temperature structure



- Yes, for the stratosphere
- But no for the mesosphere – Note the cold summer mesopause region!
- This is caused by the impact of breaking gravity waves (wind deceleration and adiabatic cooling) – see later
- It shows that coupling between radiative heating and dynamics is very important

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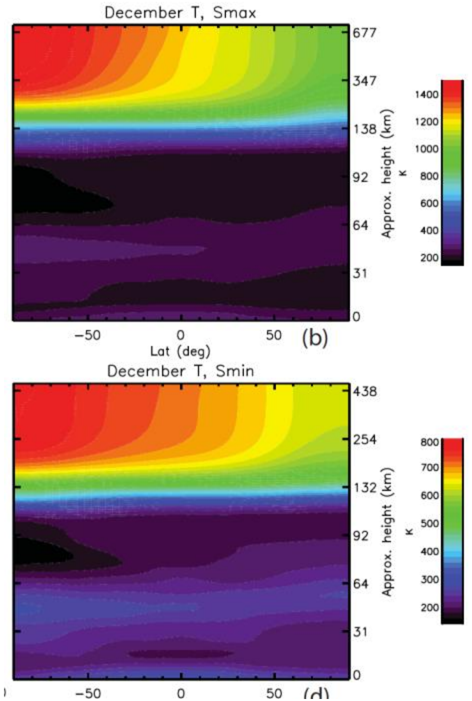
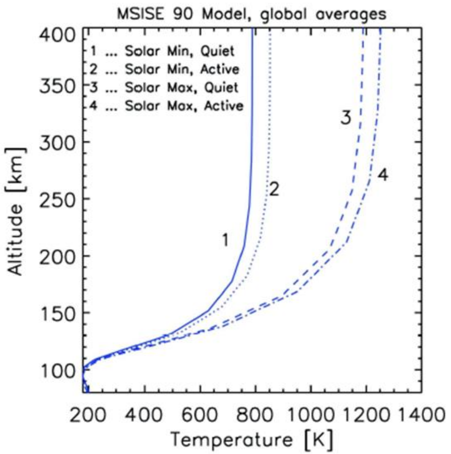
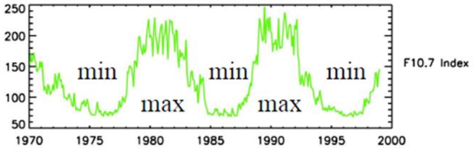
Thermosphere temperature structure



WACCM-X (Liu et al, 2018)

- Similar plot but extended to > 400 km
- Structure switches back to warm summer / colder winter above around 100 km – radiative effects more dominant than below
- Also other variations due to solar input – diurnal cycle and solar cycle
- Note large rise in T above ~100 km followed by switch to asymptotic structure (molecular diffusion suppresses gradients)
- Radiative heating plays a strong role, but other heating processes important, too





Solar flux intensity varies with ~11 year cycle

Other heating in the thermosphere

Chemical heating

FUV / EUV radiation leads to Photodissociation and Photoionisation of constituents like O2

- Example shown is for O2 dissociation – which takes place in the Schumann-Runge bands and continuum and Lyman-alpha
- Also O photoionisation to O+

Reaction
$O_2 + h\nu \rightarrow O(^3P) + O(^3P)$
$O_2 + h\nu \rightarrow O(^1D) + O(^3P)$
$O(^3P) + h\nu \rightarrow O^+(^4S)$
$O(^3P) + h\nu \rightarrow O^+(^2D)$
$O(^3P) + h\nu \rightarrow O^+(^2P)$
$O(^3P) + h\nu \rightarrow O^+(^4P^e)$
$O(^3P) + h\nu \rightarrow O^+(^2P^e)$

Reaction
$O + O_3 \rightarrow O_2 + O_2$
$O + O + M \rightarrow O_2 + M$
$O + OH \rightarrow H + O_2$
$O + HO_2 \rightarrow OH + O_2$
$H + O_2 + M \rightarrow HO_2 + M$
$O + O_2 + M \rightarrow O_3 + M$
$H + O_3 \rightarrow OH + O_2$
$O(^1D) + M \rightarrow O + M$
$M = N_2$
$M = O_2$
$N + NO \rightarrow N_2 + O$
$N(^2D) + O_2 \rightarrow NO + O$
Ion reactions

Subsequent Recombination of products (eg O) is an exothermic reaction leading to chemical heating

- In example shown (for lower thermosphere) O, H, N and ion recombination are most important heating reactions

- **Joule heating** is frictional heating largely associated with electric currents in the thermosphere.
- **Auroral heating** is due to energetic particle precipitation into high latitudes
- Both generally quite minor in quiet times
- But during geomagnetic storms can be dominant at high latitudes – increased particle precipitation and increased electric currents (leading to increased heating)

Energetics budget

Burrell et al 2015

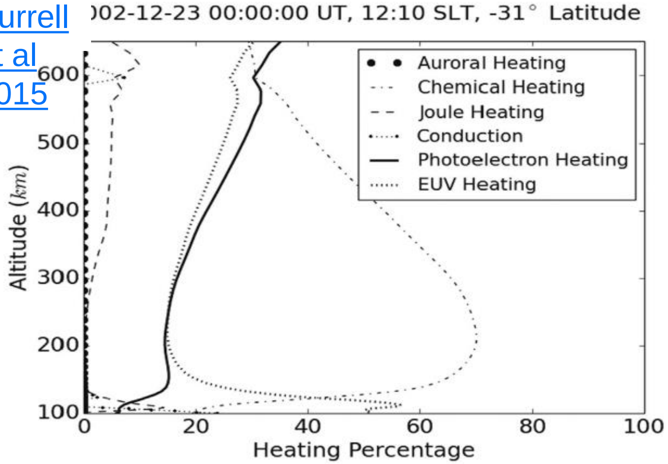
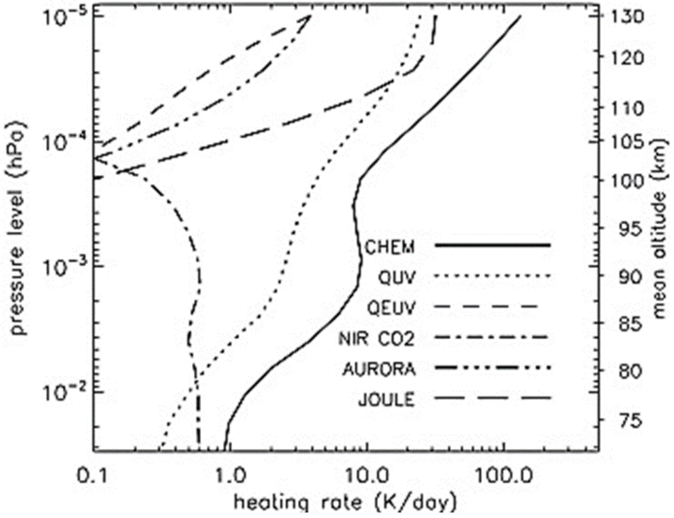


Fig. 1. Sample percentage of main heating sources at mid-latitudes.

- Lower down, generally dominated by EUV heating
- Higher up, chemical heating takes over
- ~representative of global picture - but actually spot value at middle latitudes, so don't expect any Joule / auroral heating processes

Marsh et al 2007



- Global mean July solar min for lower thermosphere
- JH and auroral heating seen but will be higher at high lats
- Exothermic heating important
- Direct UV heating important at these heights; EUV role growing at higher altitudes

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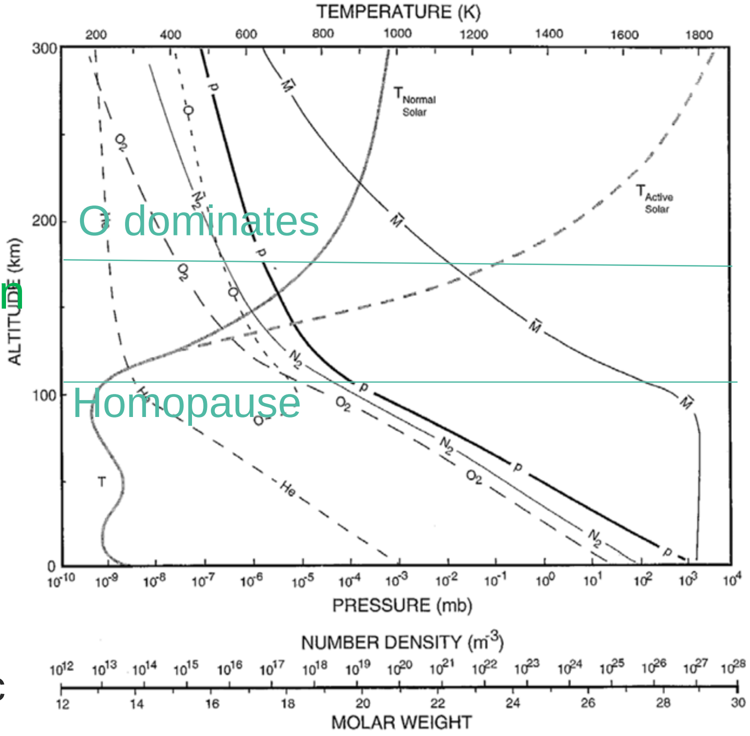
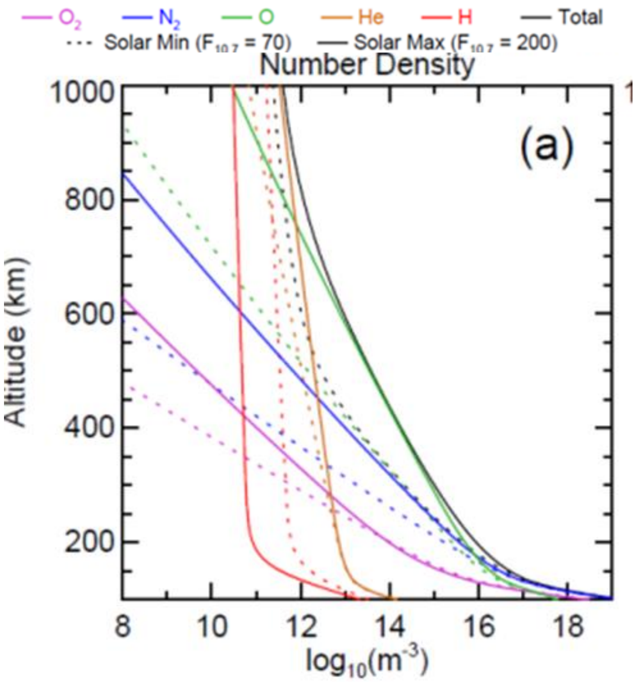
Homopause

- Below homopause (~105 km) eddy diffusion (turbulent mixing) dominates
- Above it, molecular diffusion – separation of constituents by particle mass

- Note how composition changes significantly only at heights above ~100 km
- Above ~180 km atomic oxygen is the major constituent





At 200-300 km O (lightest) dominates while O2 and N2 (heavier) fall off. Increased relative abundances of lighter elements (O, He, H) above around 550 km

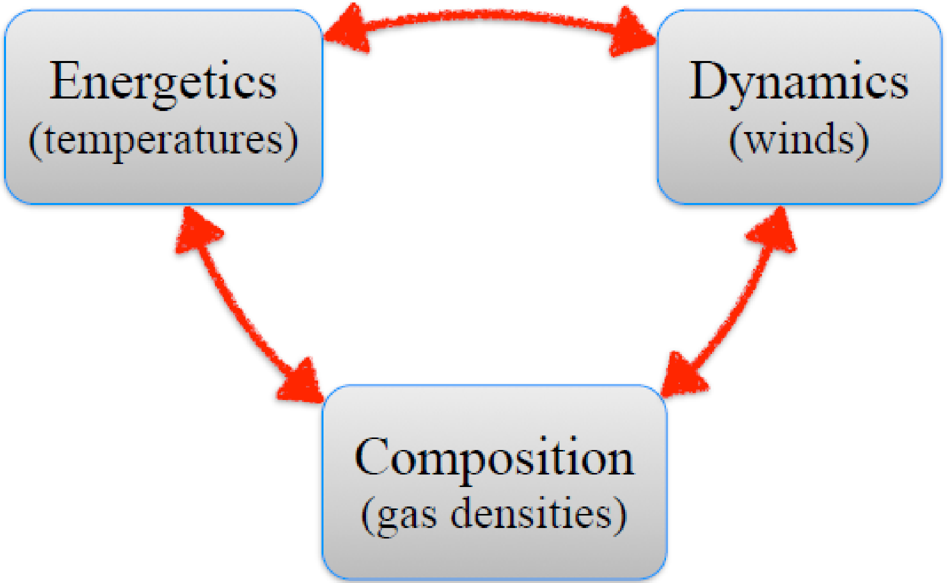
Summary of energetics

Region	*Energy sources*	*Energy sinks*
Mesosphere	• Some UV absorption by O_3 (lower heights) • Heat transport down from thermosphere (minor, top heights only)	• IR cooling by CO_2, H_2O, OH
Thermosphere	• Absorption of UV (120-200 nm) dissociating O_2 • Absorption of EUV (20-100 nm) ionising O, O_2, N_2 • Joule heating by auroral electrical currents • Particle precipitation from magnetosphere • Internal redistribution from advection and adiabatic heating	• Thermal downward conduction into the mesosphere • IR cooling by NO and CO_2 (after geomagnetic storms only) • Internal redistribution from advection and adiabatic cooling

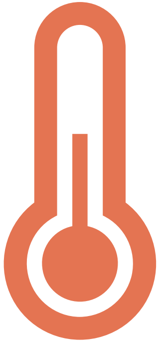
Coldest place on Earth

Hottest place in atmosphere

Everything is coupled!



Part 1: Thermal structure



Questions?

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Part 2: Dynamics

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- Navier-Stokes equations represent fluid flow on a rotating sphere
- Momentum, mass continuity, thermodynamics
- Valid from surface to exobase

Mesosphere / Thermosphere Dynamics

Momentum equation (Navier Stokes):

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

Core equation for a neutral fluid

(no charge, no magnetic materials)

Mesosphere / Thermosphere Dynamics

Momentum equation (Navier Stokes):

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

Coriolis term

pressure gradient

gravity

viscosity

ion drag

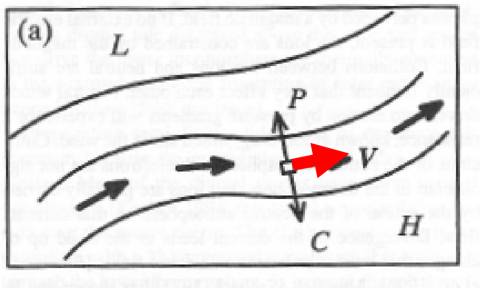
$$\frac{d\mathbf{U}}{dt} = \frac{\partial\mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\,\mathbf{U}$$ … Eulerian derivative

advection

Pressure gradients and **Ion drag** are **external forces**, the rest are **internal**

Momentum balance

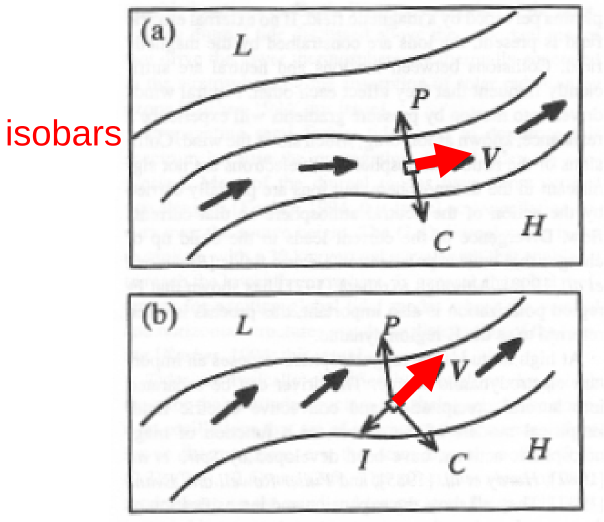
isbars



Geostrophic balance

- pressure force balanced by Coriolis P = C
- wind flow along isobars
- applies in troposphere, stratosphere and to some extent in mesosphere

Momentum balance



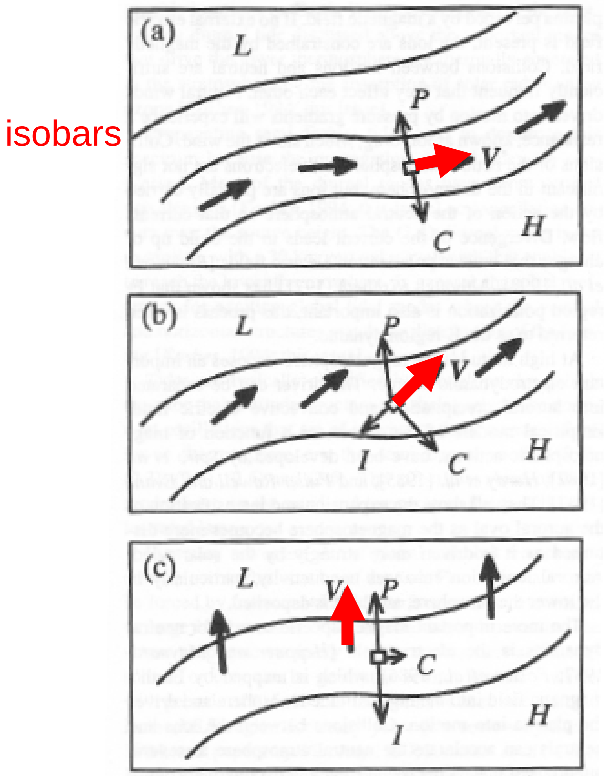
Geostrophic balance

- pressure force balanced by Coriolis **P = C**
- wind flow along isobars
- applies in troposphere, stratosphere and to some extent in mesosphere

Inclusion of small friction

- pressure force balanced by partly Coriolis and other drag force (viscosity, waves)
- some wind flow across isobars
- applies in mesosphere & lower thermosphere

Momentum balance



(Fuller-Rowell, 1995)

Geostrophic balance

- pressure force balanced by Coriolis **P = C**
- wind flow along isobars
- applies in troposphere, stratosphere and to some extent in mesosphere

Inclusion of small friction

- pressure force balanced by partly Coriolis and other drag force (viscosity, waves)
- some wind flow across isobars
- applies in mesosphere & lower thermosphere

Inclusion of ion drag

- pressure force balanced by ion drag & both are larger than Coriolis
- wind flow perpendicular to isobars
- applies in thermosphere, esp. at high latitudes

Atmospheric waves

- Middle atmosphere structure and dynamics cannot be understood without considering presence of atmospheric waves
- These release momentum into background atmosphere

Type	Origin	Properties	Dissipation / breaking altitude
Planetary Waves	Forced (orography, low level heating) and free modes (resonant oscillations)	2-30 day period Easterly / quasi-stationary Vertically propagating Global scale waveno 1-3 in strat / mesosphere	Typically < 100 km Some PW signatures seen in thermosphere
Gravity Waves	Orography, convection, fronts, etc	Period: minutes-hours Scale – typically 10-1000 km **Easterly and westerly**	Stratosphere and mesosphere (primary) Lower thermosphere (secondary)
Tides	Solar:Thermal heating (H_2O in troposphere, O_3 in stratosphere, O_2 and N_2 in thermosphere) Lunar: gravitational	6,8,12,24 h	Stratosphere / mesosphere / lower thermosphere

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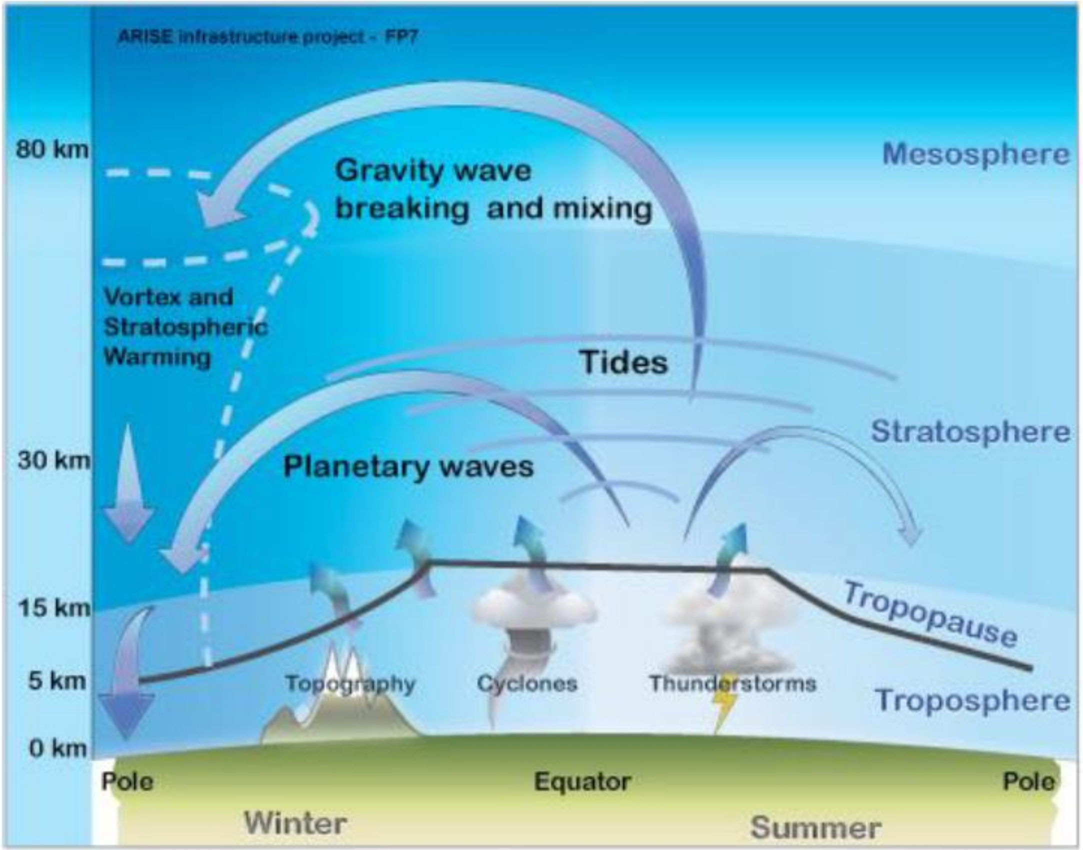
Atmospheric waves

- Upward propagating waves break and dissipate, releasing energy and momentum (and inducing a meridional circulation as a result)
- This provides a vertical coupling mechanism
- Also responsible for structure in middle atmosphere



Gravity wave momentum deposition

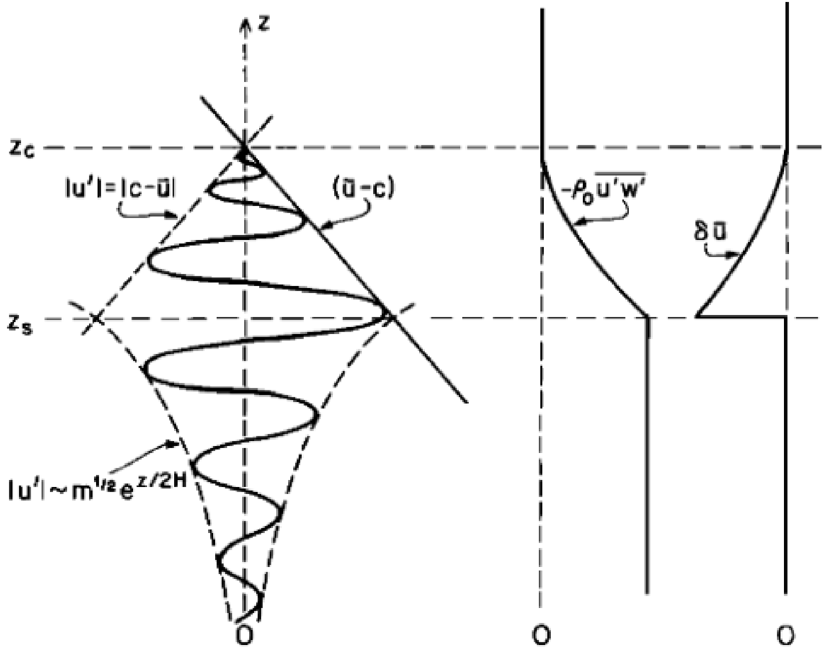


Fig. 9. Schematic of the growth with height and saturation of a gravity wave due to convective instability. Wave damping produces both a divergence of the vertical flux of horizontal momentum and an acceleration of the mean flow toward the phase speed of the wave. Deceleration and diffusion cease above the critical level ($z = z_c$) in the linear theory.

Fritts (1984)

Gravity wave grows as density decreases

Saturation reached when wave statically unstable, which also means u'+$\bar{u}$ > c (phase speed) at height z_s

Above z_s u' -> 0 and GW deposits momentum against mean flow until critical height z_c, where $\bar{u} - c = 0$ is reached

Also: waves absorbed at critical line where $\bar{u} = c$ so spectrum of eastward + westward waves travelling through westward wind shall be filtered so that only (largely) eastward waves remain

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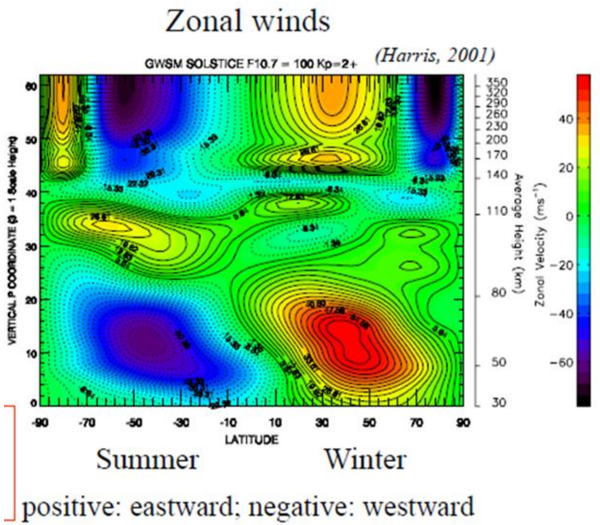
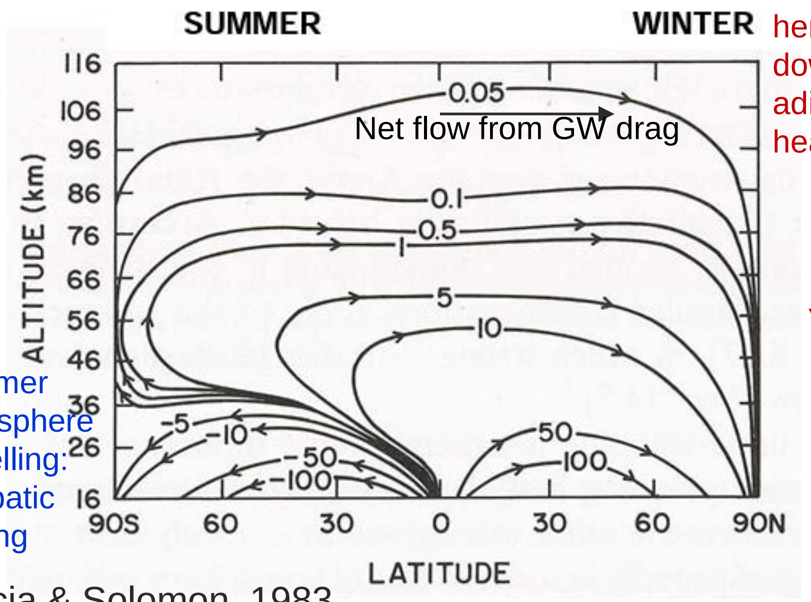
Gravity waves: so what? Closure…



Winter hemisphere downwelling: adiabatic heating

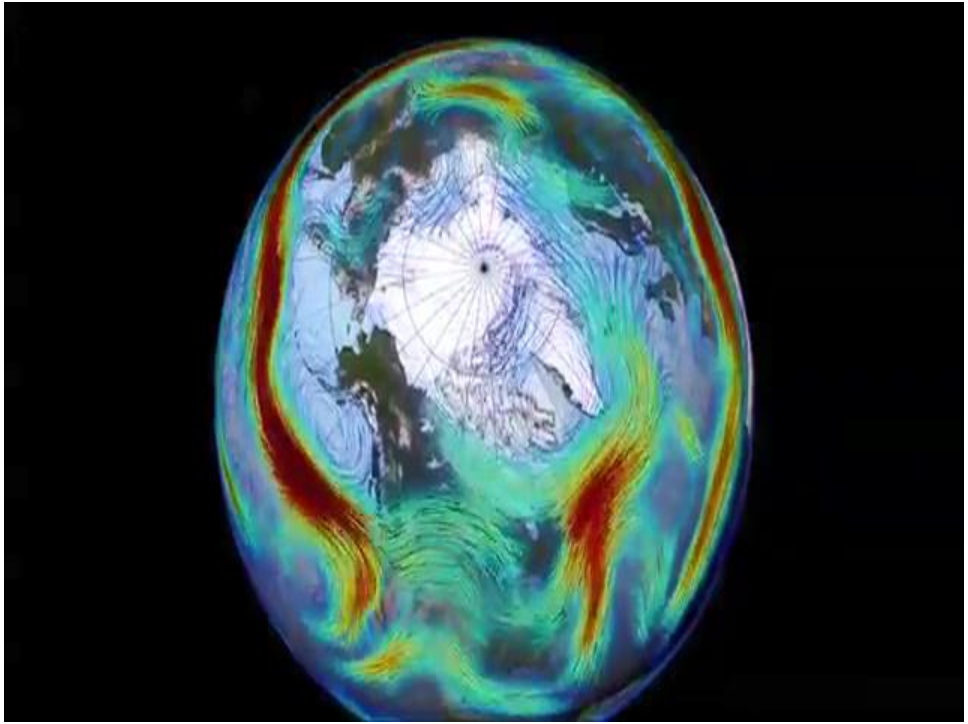


Summer hemisphere upwelling: adiabatic cooling

Garcia & Solomon, 1983

- Breaking of gravity waves results in deceleration of mesospheric jets
- Associated momentum deposition induces a pole-to-pole circulation in mesosphere with summer to winter flow, ascent (descent) over summer (winter) pole and associated adiabatic cooling (heating)
- Explains those cold summer temps!

Planetary waves



https://www.weather.gov/jetstream/longshort

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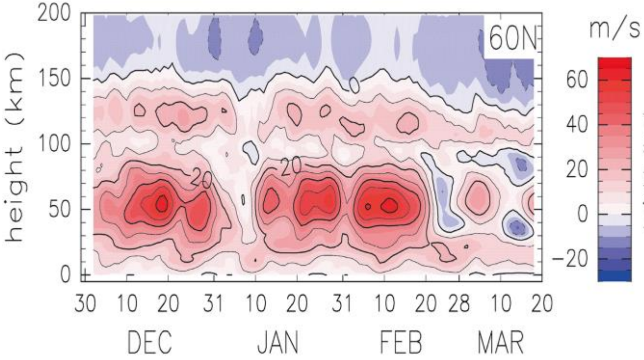
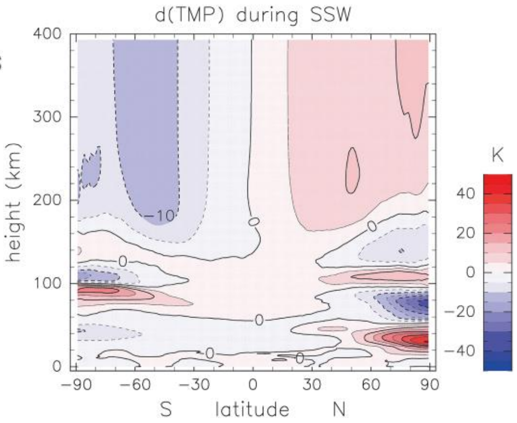
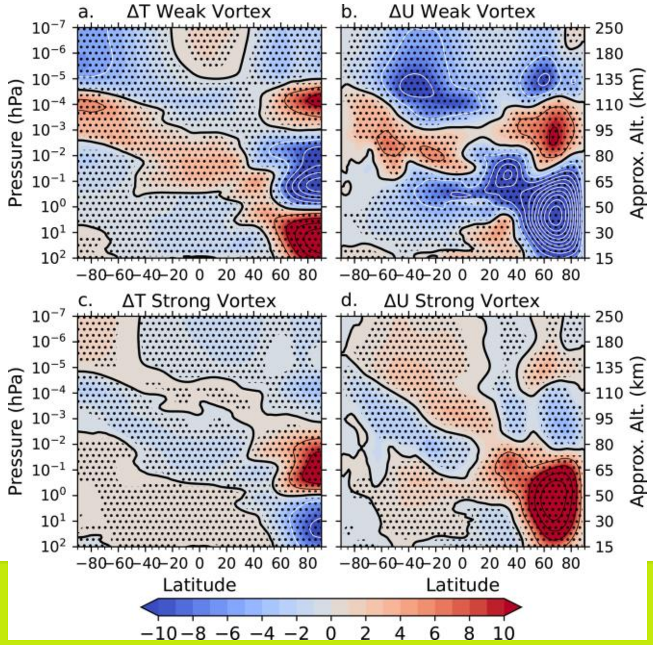
Planetary waves

- Planetary waves generated in the troposphere are generally blocked in the summer stratosphere and only larger ones (w1-3) remain in the winter stratosphere
- PWs => stratospheric warming / variations in jets
- Can also have impacts in MLT - cooling (warming) in mesosphere (thermosphere) for weak vortex?
- Most PWs dissipate by mesopause but others can be generated (eg PW / tides interaction)



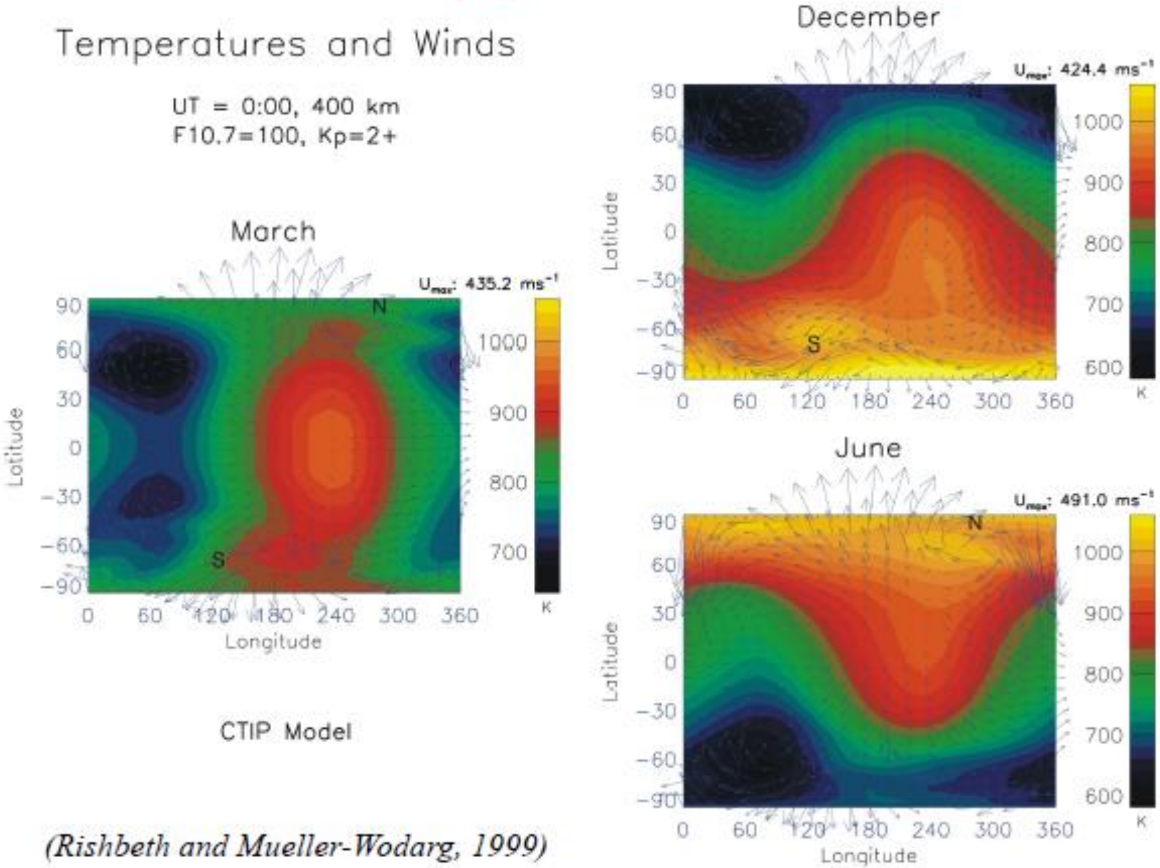


Miyoshi et al (2015)



Pedatella (2023)

Upper Thermosphere



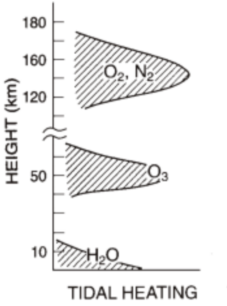
(Rishbeth and Mueller-Wodarg, 1999)

Winds flow **perpendicular** to isobars.

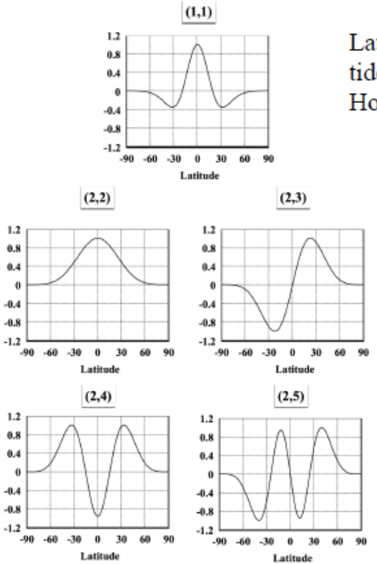
At high latitudes strongly enhanced winds due to ion drag

- Day night T diffs are very large > 200 K in March; > 100 K at solstices
- Solstice winter / summer differences > 400 K

Atmospheric tides

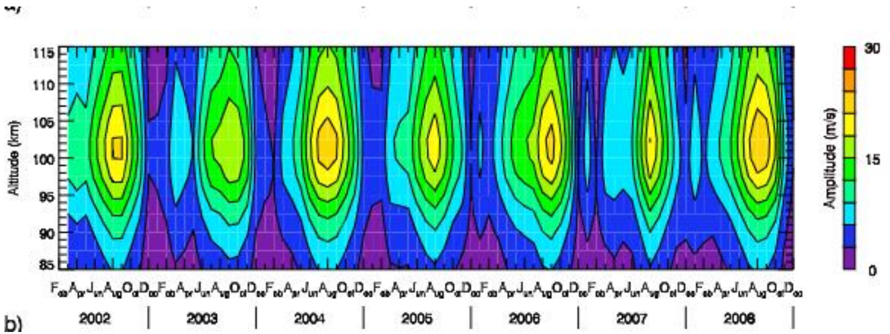


Vertical distribution of the drivers of thermal tides

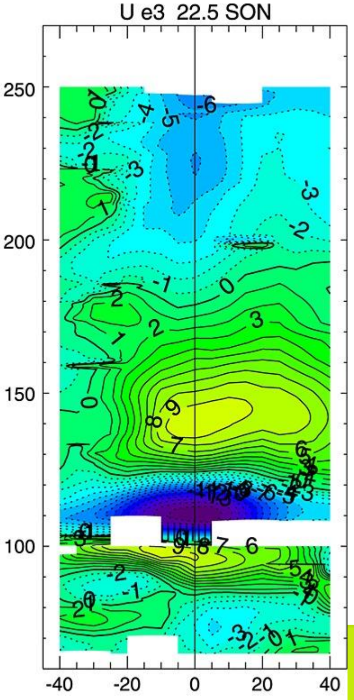


Latitudinal structure of tides, as described by Hough modes

Name	Description
(1,1)	*Diurnal, symmetric*
(2,2)	*Semidiurnal, first symmetric*
(2,3)	*Semidiurnal, first asymmetric*
(2,4)	*Semidiurnal, second symmetric*
(2,5)	*Semidiurnal, second asymmetric*



DE3 u amplitude from SABER (Oberheide et al 2009) and WINDII (Lieberman et al, 2013)



Akmaev et al 2008

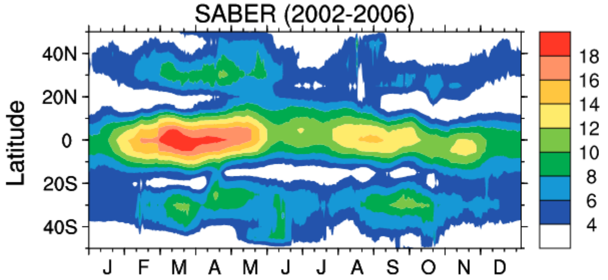


Figure 1. Diurnal migrating temperature amplitude near 100 km as a function of latitude and season: (top) WAM simulations and (bottom) SABER observations

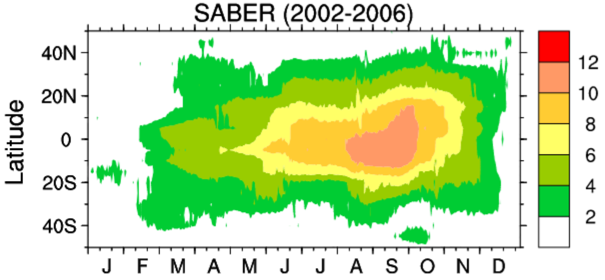
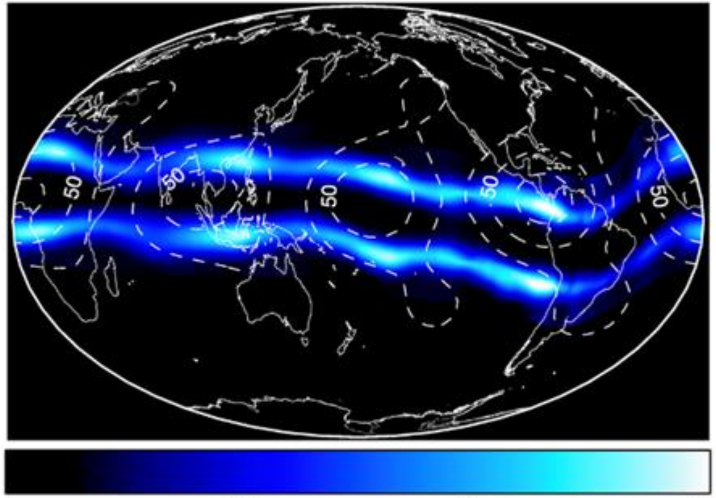


Figure 3. Same as in Figure 1 but for the diurnal nonmigrating eastward tide with zonal wavenumber 3 (DE3) near 116 km

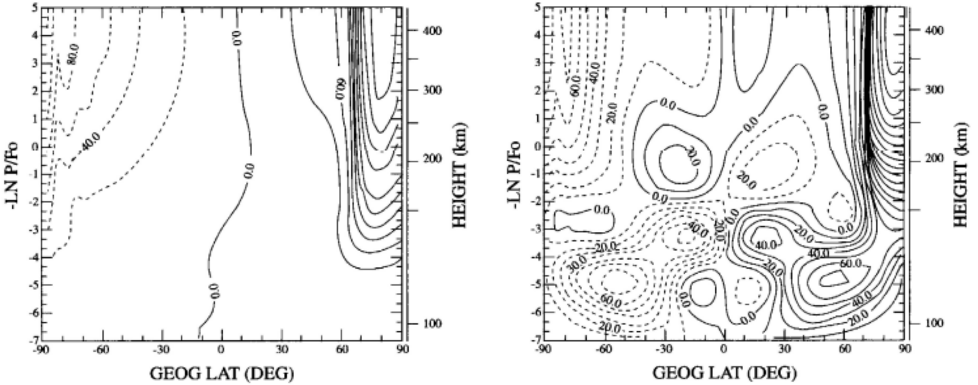
Effects of atmospheric tides

Lower atmosphere / lower thermosphere / ionosphere coupling



W-4 structure (DE3 + (1,1) seen at 115 km (contours) and in ionosphere at ~300 km (contours) [Immel et al, 2006]

No tides | Including tides



Zonally averaged meridional winds at 70°W and 18:00 UT for quiet-time conditions with (right) and without (left) tidal oscillations. Contours are positive southward.

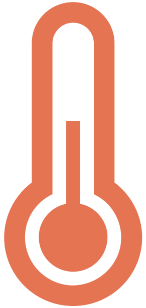
Note how the **tides dominate** the low- to mid latitude thermosphere!

Momentum deposition from tides mainly from diurnal (<120 km) and semi-diurnal (>120 km)

Part 2: Dynamics

Questions?

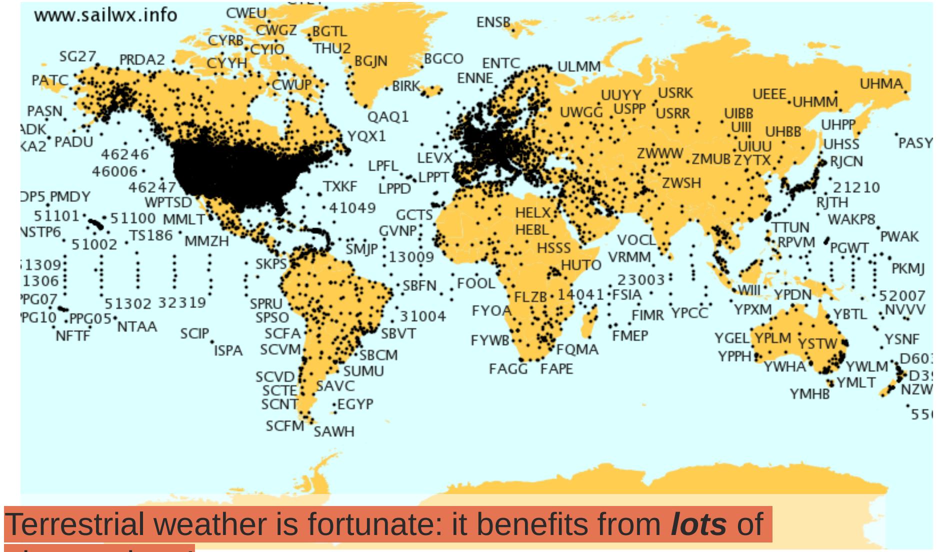
Part 3: Observations, Modelling and Forecasts



Met Office

How do we study these regions?

- Worth comparing with terrestrial weather
- Observations give key insights
- Data assimilation of observations also helps models represent reality – lets models be used to provide skilful forecasts.

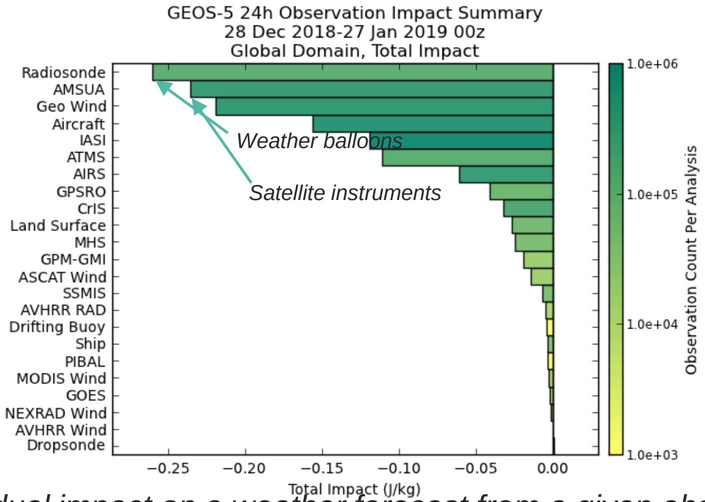


Terrestrial weather is fortunate: it benefits from ***lots*** of observations!

Observing stations network coverage is impressive

Global satellite coverage (not shown) even more so!

Many different types of observations help contribute to skilful weather forecasts

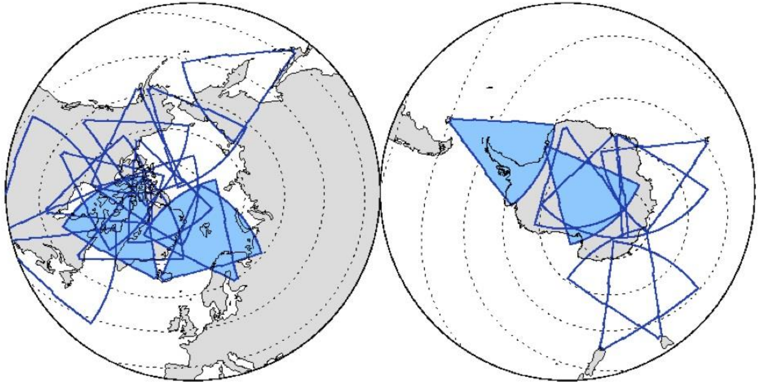


Individual impact on a weather forecast from a given obs type

NASA, 2019

Airglow: measure with Fabry-Perot interferometers

SuperDARN coherent scatter radar network



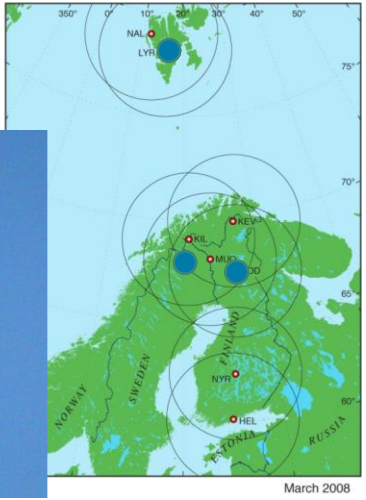
How do we study these regions?

Ground-based resources: radars, ionosondes, optical instruments, magnetometer networks, rocket launches (!)

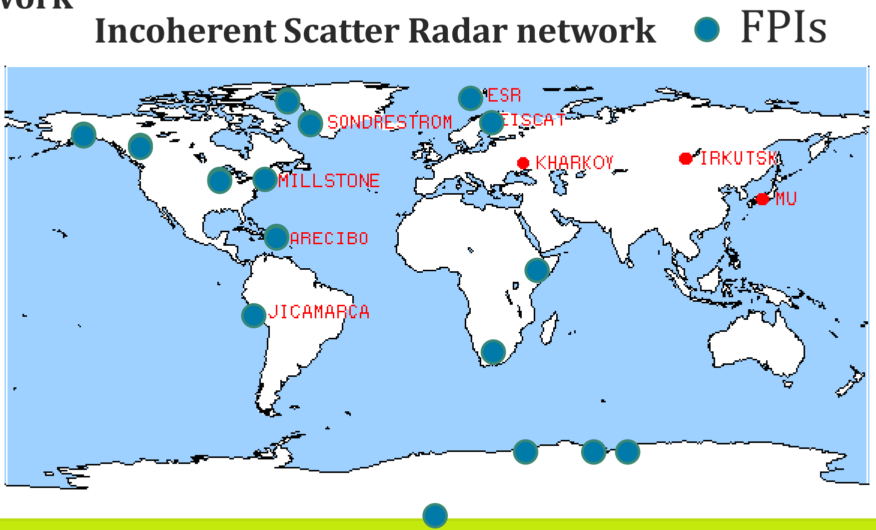
Poker flats rocket launch

Infer winds from meteor trails

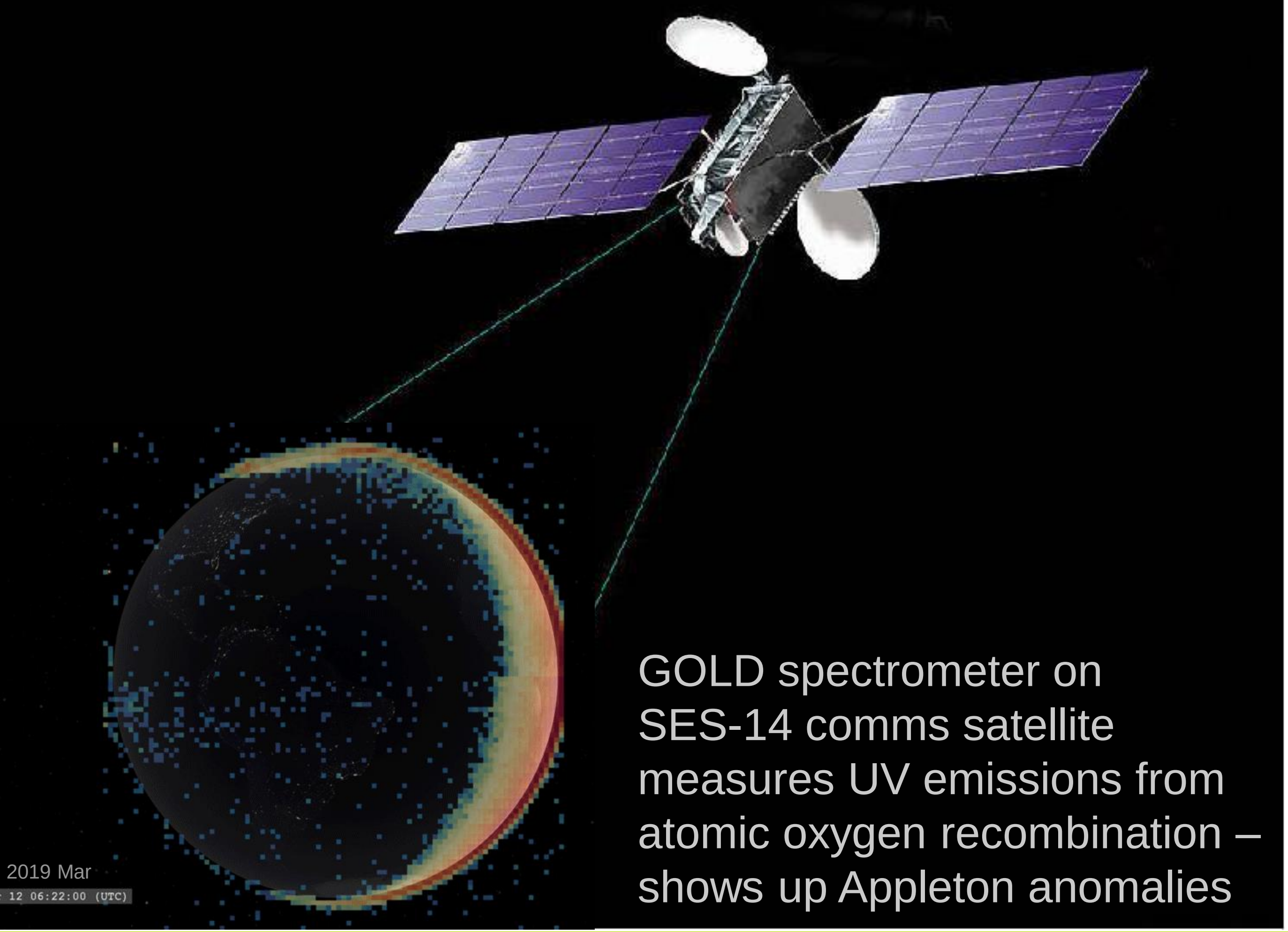
MIRACLE all-sky camera network



Incoherent Scatter Radar network



Far fewer ground-based resources for upper atmosphere-ionosphere monitoring



GOLD spectrometer on SES-14 comms satellite measures UV emissions from atomic oxygen recombination – shows up Appleton anomalies

Satellites

Some neutral remote sensing *is* possible: TIMED, GOLD, SABER, ICON, …

Other in-situ data: GOCE, CubeSats,…

But these research missions aren't (yet) suited for operations

Data can't be used like operational radiance products lower down, which are assimilated real-time to improve models, make forecasts

Airbus DS, NASA's Scientific Visualization Studio/Tom Bridgman/Joy Ng

Observational Needs for Thermospheric Forecasts

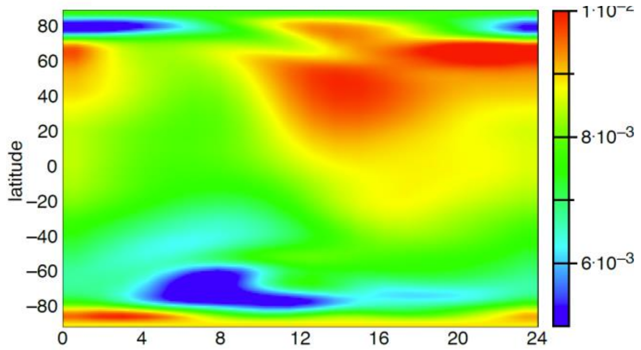
Observations of temperature, wind and density are required, ideally with

- Resolution of 100-500 km (horizontal), 5-15 km (vertical, lower thermosphere), 20-100 km (vertical, upper thermosphere)
- Observing cycle 5s-30 min and timeliness < 30-60 min
- Far from the case right now!

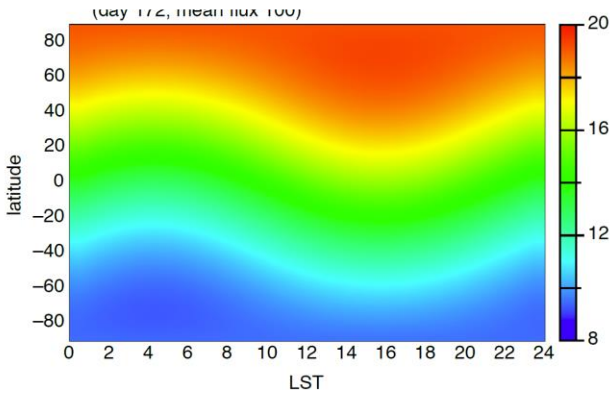
Layer	Assessment	Comments
T (Hi Thermo)	Poor	Only a few sparse FPI observations are available. Poor timeliness.
T (Low Thermo)	Marginal	Optical Spectrograph and InfraRed Imaging System data are available, but they do not cover whole vertical range and have poor timeliness.
Density (Hi Thermo)	Marginal	Swarm meets most requirements, apart from timeliness and vertical resolution. SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness
Density (Low Thermo)	< Marginal / Marginal	SSUSI and SSULI may meet requirements, but no information is available on accuracy, observational cycle and timeliness.
U (High Thermo)	Poor	Only a few sparse FPI observations. Poor timeliness. Accelerometer winds have too large errors to be useful. Region partially covered by new ICON observations.
U (Low Thermo)	Poor	Data gap (daytime) addressed by ICON. No other current observations.

Thermospheric Models

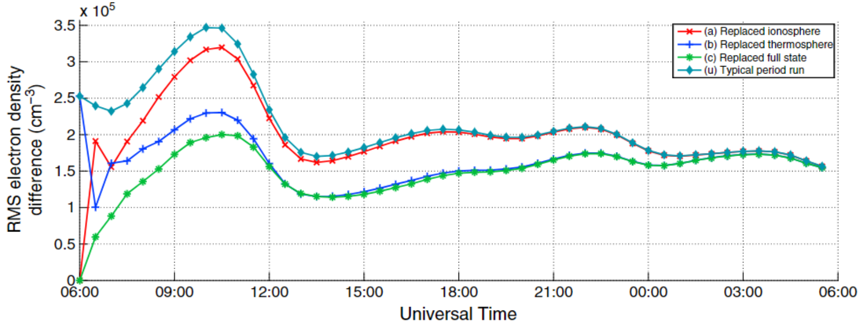
UCL CMAT2 (day 172, mean flux 100)
temperature gradient (K/km) at 120km



DTM2012 (day 172, mean flux 100)
temperature gradient (K/km) at 120km



- **Semi Empirical (eg DTM, MSISE00):** Trained on historical data, driven by solar and geomagnetic proxies. Often used in ops (eg Met Office). Low spatial resolution and poor for events not often seen in obs (eg Starlink)
- **1st principles (thermos/iono):** T-I coupling (better evolution), lower boundary in stratosphere / mesosphere. Add in DA (TIEGCM AENeAS) for future MetO ops

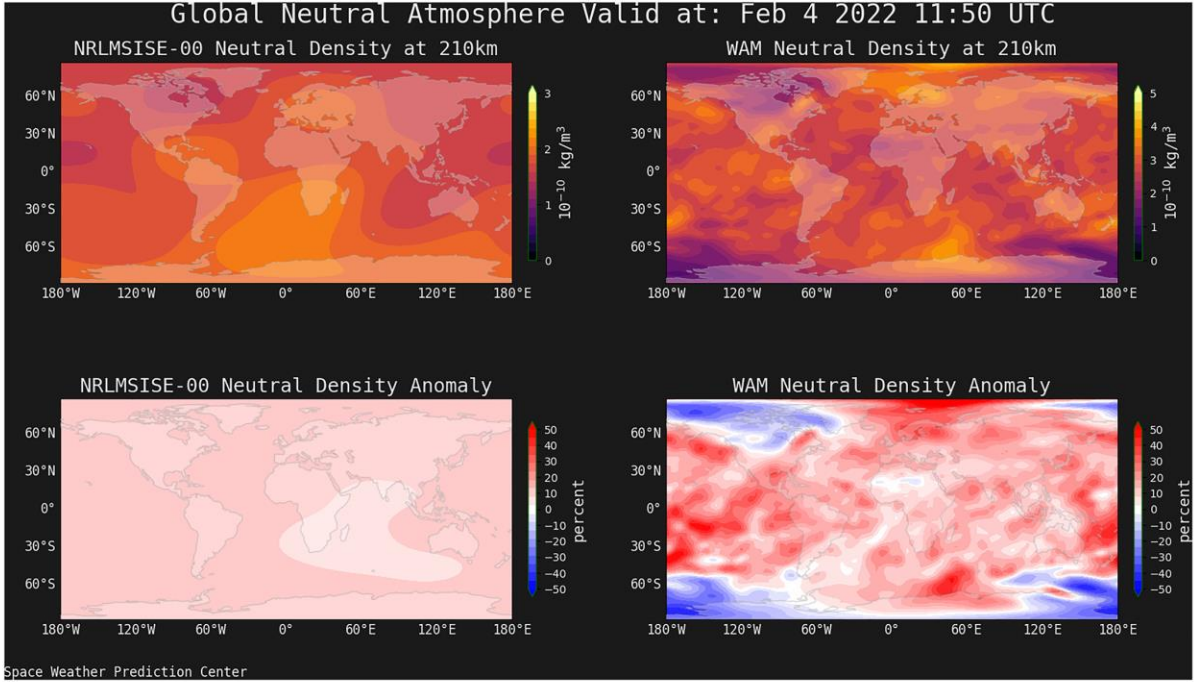


Chartier et al 2013

- **1st principles (whole atmosphere):** Comprehensive coupling from low to high. NOAA operational model (WAM) produced reasonable representation of Starlink event but limited DA currently

Thermospheric Models

- **Semi Empirical** can be poor for geomagnetic storms compared to 1st **principles models** eg Starlink event



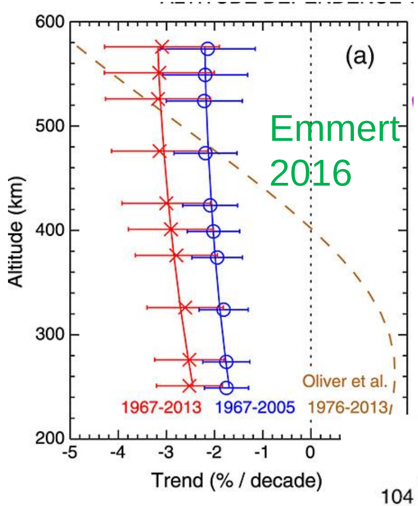
Global neutral density and density anomaly at 210 km simulated by MSIS-00 (left) and coupled WAM / IPE (right) at 11:50 UTC on 4 February 2022. Fang et al, 2023

Met Office

Thermospheric Climate Change

Impact of climate change seen as global warming in troposphere, but as cooling in strat / meso / thermosphere. => shrinking of thermosphere and a reduction in thermospheric density, due to contraction of the cooling atmosphere.

- Lower thermosphere trend ~ -2 to -4 K/year and -3% /decade in density
- At 400 km typical density trend ~ −2%/decade.
- Can vary with solar cycle, altitude, latitude
- If 1.5°C global warming target is met, objects in LEO will have orbital lifetimes ~ 30% > comparable objects from year 2000 (Brown et al, 2021)



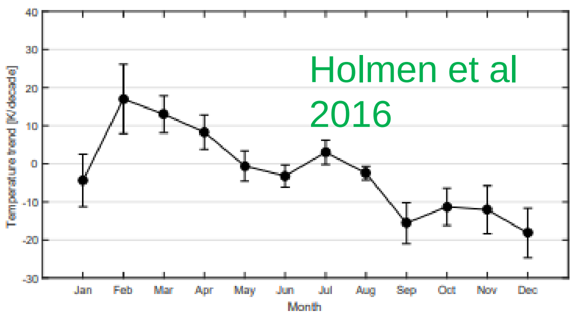
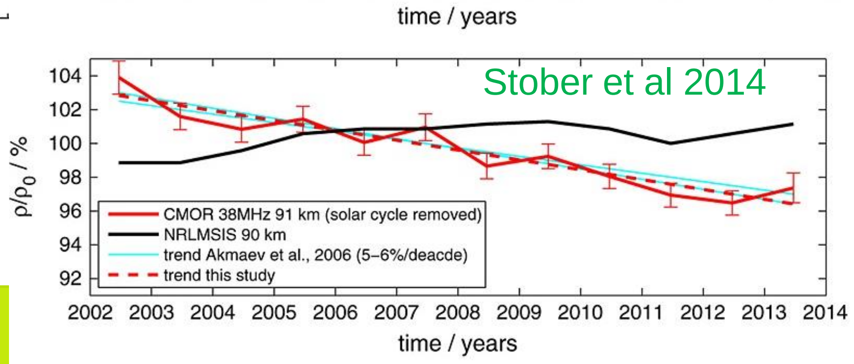


Figure 8. Monthly temperature trends at 90 km altitude over Tromsø. Standard deviations are given as error bars.



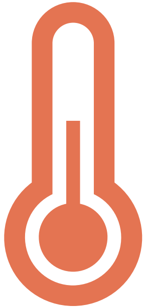
Further resources

Key texts treating the mesosphere/thermosphere regions:

- Andrews, Holton and Leovy, *Middle Atmosphere Dynamics*, Academic Press, New York, 1987
- Banks, P.M. & G. Kockarts, *Aeronomy*, Academic Press, New York, 1973
- Brasseur, G and S. Solomon, *Aeronomy of the Middle Atmosphere*, D. Reidel Publishing, 2nd Edition, 1986
- Chamberlain J. W., and D. M. Hunten, *Theory of Planetary Atmospheres*, Academic Press, New York, 1987
- Chapman, S. C. and R. S. Lindzen, *Atmospheric Tides*, D. Reidel, Dordrecht, 1970
- Fritts, D.C (1984) Gravity wave saturation in the middle atmosphere: A review of theory and observations, Rev. Geophys., 22, 275–308
- Johnson, R. M. and T. L. Killeen (Eds), *The Upper Mesophere and Lower Thermosphere: A Review of Experiment and Theory*, American Geophysical Society, Geophysical Monograph 87, 1995
- Rees, M. H., *Physics and Chemistry of the Upper Atmosphere*, Cambridge University Press, Cambridge, UK, 1989
- Wang, W., Y. Zhang, Y., and L. J. Paxton (Eds), Upper Atmosphere Dynamics and Energetics, American Geophysical Union, Geophysical Monograph, 2021, DOI:10.1002/9781119815631

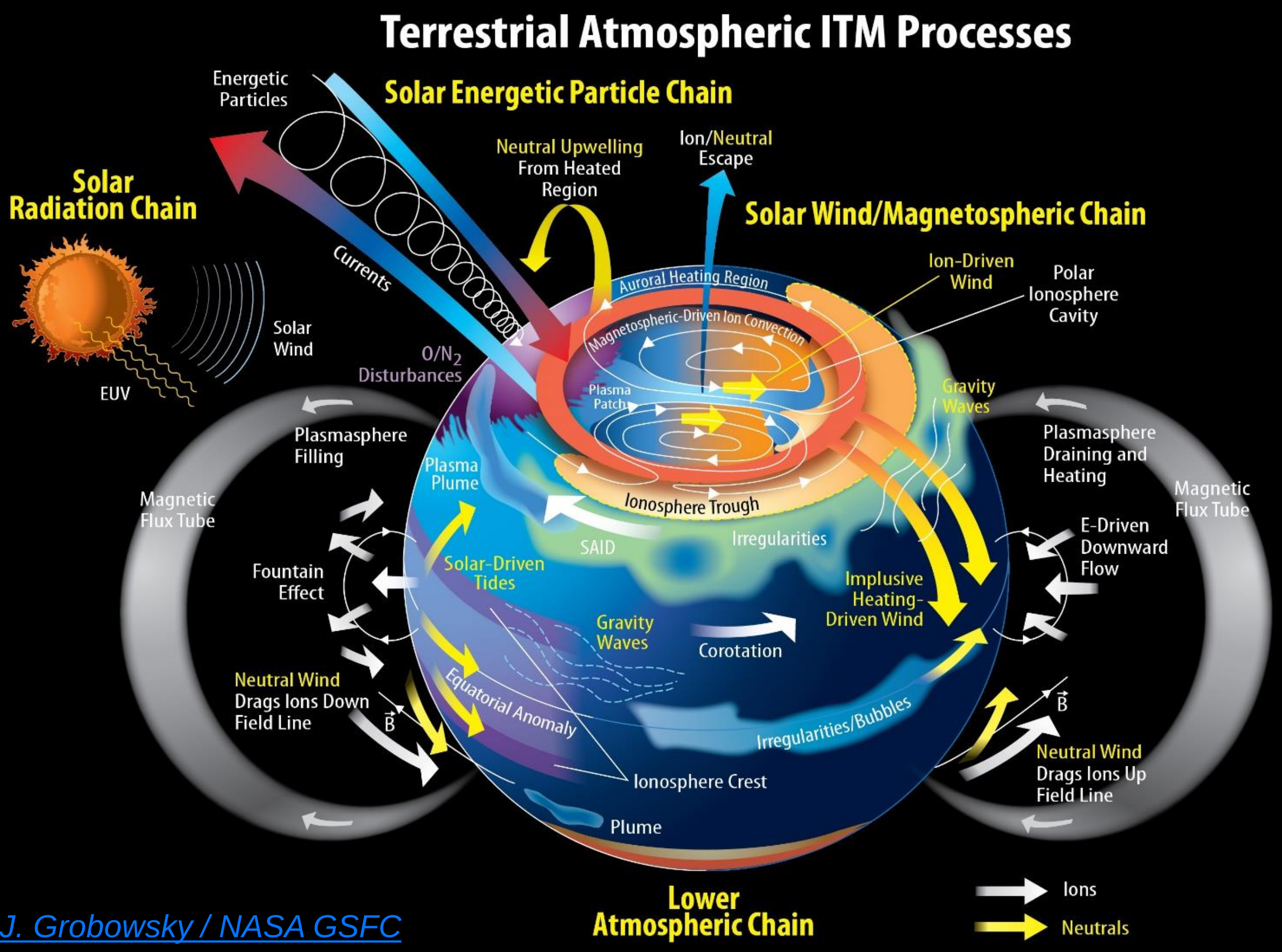
- The MSIS empirical atmosphere model (surface to thermosphere) is available at NASA CCMC:
    - https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php

Extra slides



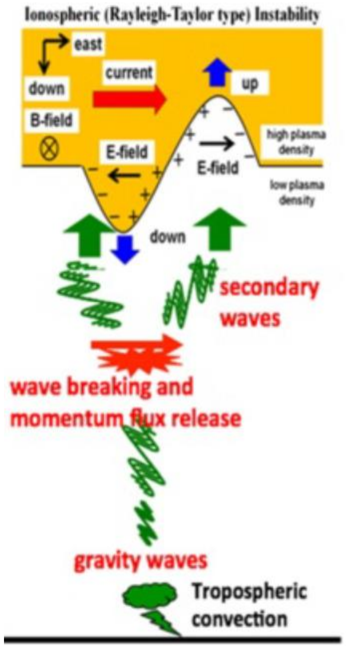
Big picture

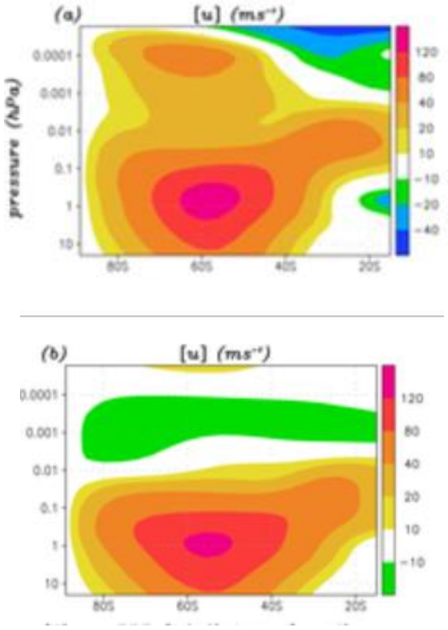
- *Everything* is coupled!
- Outward to the solar wind and sun
- Downward to the lower atmosphere
- Between ITM spheres
- Internal variability!
- So very complex
- Lots of interacting processes…



J. Grobowsky / NASA GSFC

Secondary gravity waves

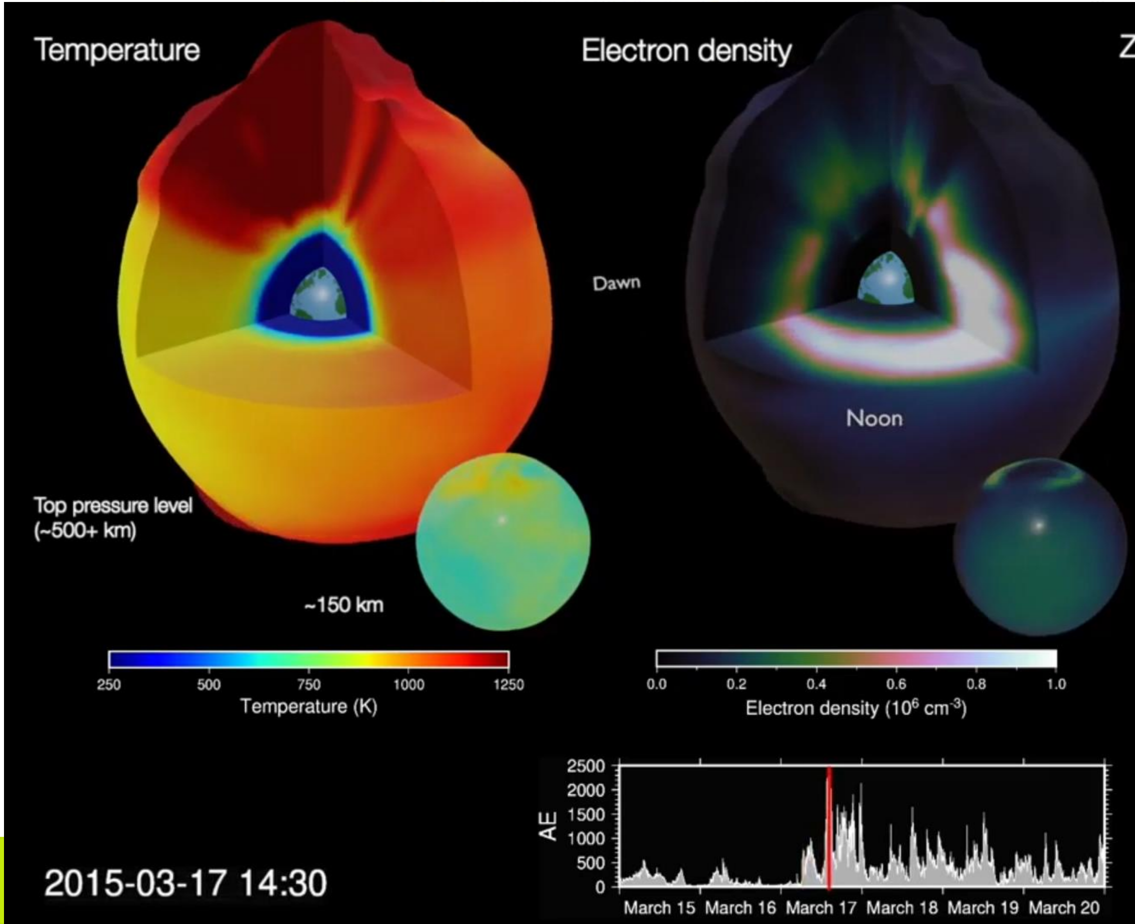




- Classical cartoon can make one assume gravity waves stop where they break in the mesosphere
- Caution! There's good observational evidence (radar data) for gravity wave influence further up
- Basic mechanism seems to be generation in situ higher up – secondary gravity waves generated by intermittent breaking of primary waves near s/pause and associated instability

Tsuda et al 2015; Becker and Vadas 2018

Space weather response of thermosphere



St Patrick’s day storm simulated with WACCM-X
Eelco Doornbos YouTube

Time scales

The analysis of time scales in a system allow for quick "back of the envelope" estimates of what the dominant processes are

Eddy diffusion: $$\tau_K = \frac{H^2}{K}$$

Molecular diffusion: $$\tau_D = \frac{H^2}{D_i}$$

Horizontal winds: $$\tau_{wind,\ horiz} = \frac{dist}{U_{horiz}}$$

Vertical winds: $$\tau_{wind,\ vert} = \frac{H}{U_z}$$

Chemical, production: $$\tau_{chem,\ prod} = \frac{1}{J}$$ $$n_i + h\,\nu \xrightarrow{J} n_j$$

Chemical, 2-body reaction: $$\tau_{chem,\ 2-body} = \frac{1}{L\ n_j}$$ $$n_i + n_j \xrightarrow{L} n_k + n_l$$

H … scale height
K … eddy diff. coeff.
D_i … molec. diff. coeff.
dist … typical horiz. distance
U_{horiz} … horiz. wind speed
U_z … vertical wind speed
J … rate coefficient [1/sec]
L … rate coefficient [m^3/sec]

Time scale analysis

Examples:

$\tau_D \ll \tau_{wind}$	Molecular diffusion is more effective than winds in changing composition $\Rightarrow$ diffusive balance holds, winds don't matter.
$\tau_K \ll \tau_{chem}$	Turbulent mixing is more effective than chemical changes, so the gas distribution is strongly affected by turbulence
$\tau_{chem} \approx \tau_{wind}$	Chemical changes and winds are equally important in changing the composition.

Met Office

Continuity equation

$$\frac{dn_i}{dt} = P_i - n_i\, L_i - \frac{\partial \Phi_i}{\partial z}$$

- $\frac{dn_i}{dt}$
- P_i: production of gas i due to chemistry
- $n_i L_i$: loss of gas i due to chemistry
- $\frac{\partial \Phi_i}{\partial z}$: vertical flux of gas i due to diffusion

$$\frac{dn_i}{dt} = \frac{\partial n_i}{\partial t} + \mathbf{U} \cdot \nabla\, n_i$$

- $\mathbf{U} \cdot \nabla\, n_i$: advection (transport by winds)

n_i … density of gas i
K … Eddy diffusion coefficient
D_i … molecular diffusion coefficient
H_i … scale height of gas i
H_0 … mean scale height of atmosphere
Φ_i … flux of gas i
$\mathbf{U}$ … wind vector

$$\Phi_i = -(K + D_i)\, n_i - D_i\, n_i \left(\frac{1}{H_i} - \frac{1}{H_0} \right)$$

… Diffusion equation (without thermal diffusion)

Met Office

Vertical winds and composition

- Upward vertical *divergence* winds (winds relative to pressure levels, as opposed to simple expansion of the atmosphere) transport gases from lower to higher altitudes.
- Gases at lower heights are richer in molecular constituents, so the upward winds cause gases higher up to be relatively more molecular.
- So, **upward** winds cause a **decrease** in the O/N_2 ratio.
- The O/N_2 ratio is useful for understanding ionospheric electron densities

Key quantity impacting ionosphere! →