Title:	The Stratosphere and its Coupling to the Troposphere and Beyond
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The Stratosphere and its Coupling to the Troposphere and Beyond

Synonyms

Middle atmosphere

Definition

As illustrated in Figure 1, the Earth's atmosphere can be separated into distinct regions, or "spheres," based on its vertical temperature structure. In the lowermost part of the atmosphere, the *troposphere*, the temperature declines steeply with height at an average rate of approximately 7° C per kilometer. At a distinct level, generally between 10-12 km in the extratropics and 16-18 km in the tropics[1], this steep descent of temperature abruptly shallows, transitioning to a layer of the atmosphere where temperature is initially constant with height, and then begins to rise. This abrupt change in the

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[1] The separation between these regimes is rather abrupt, and can be used as dynamical indicator delineating the tropics and extratropics.

vertical temperature gradient, denoted the *tropopause*, marks the lower boundary of the *stratosphere*, which extends to approximately 50 km in height, at which point the temperature begins to fall with height again. The region above is denoted the *mesosphere*, extending to a second temperature minimum between 85 and 100 km. Together the stratosphere and mesosphere constitute the *middle atmosphere*.

The stratosphere was discovered at the dawn of the 20th century. The vertical temperature gradient, or *lapse rate*, of the troposphere was established in the 18th century from temperature and pressure measurments taken on alpine treks, leading to speculation that the air temperature would approach absolute zero somewhere between 30 and 40 km: presumably the top of the atmosphere. Daring hot air balloon ascents in late 19th century provided hints at a shallowing of the lapse rate – early evidence of the tropopause – but also led to the deaths of aspiring upper-atmosphere meteorologists. Teisserence de Bort (1902) and Assmann (1902), working outside of Paris and Berlin, respectively, pioneered the first systematic, unmanned balloon observations of the upper atmosphere, establishing the distinct changes in temperature structure that mark the stratosphere.

Overview

The lapse rate of the atmosphere reflects the stability of the atmosphere to vertical motion. In the troposphere, the steep decline in temperature reflects near neutral stability to moist convection. This is the turbulent, weather layer of the atmosphere where air is close contact with the surface, with a turnover timescale on the order of days. In the stratosphere, the near zero or positive lapse rates strongly stratify the flow. Here the air is comparatively isolated from the surface of the Earth, with a typical turnover time scale on the order of a year or more. This distinction in stratification, and resulting impact on the circulation, is reflected in the nomenclature: the "troposphere" and

"stratosphere" were coined by Teisserence de Bort, the former the "sphere of change" from the Greek *tropos*, to turn or whirl, the latter the "sphere of layers" from the Latin *status*, to spread out.

In this sense, the troposphere can be thought of as a boundary layer in the atmosphere that is well connected to the surface. This said, it is important to note that the mass of the atmosphere is proportional to the pressure: the tropospheric "boundary" layer constitutes roughly 85% of the mass of the atmosphere and contains all of our weather. The stratosphere contains the vast majority of remaining atmospheric mass, and the mesosphere and layers above just 0.1%.

Why is there a stratosphere?

The existence of the stratosphere depends on the radiative forcing of the atmosphere by the Sun. As the atmosphere is largely transparent to incoming solar radiation, the bulk of the energy is absorbed at the surface. The presence of greenhouse gases, which absorb infrared light, allow the atmosphere to interact with radiation emitted by the surface. If the atmosphere were "fixed," and so unable to convect (described as a *radiative equilibrium*) this would lead to an unstable situation, where the air near the surface is much warmer – and so more buoyant – than that above it. At height, however, the temperature eventually becomes isothermal, given a fairly uniform distribution of the infrared absorber throughout the atmosphere[2].

If we allow the atmosphere to turn over in the vertical, or convect in the nomenclature of atmospheric science, the circulation will produce to well-mixed layer at the bottom with near neutral stability: the troposphere. The energy available to the air at the surface is finite, however, only allowing it to penetrate so high into the atmo-

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[2] The simplest model for this is a so-call "gray radiation" scheme, where one assumes all solar radiation is absorbed at the surface and single infrared band from the Earth interacts with a uniformly distributed greenhouse gas.

sphere. Above the convection will sit the stratified isothermal layer that is closer to radiative equilibrium: the stratosphere. This simplified view of a *radiative-convective equilibrium* obscures the role of dynamics in setting the stratification in both the troposphere and stratosphere, but conveys the essential distinction between the layers. In this respect, "stratospheres" are found on other planets as well, marking the region where the atmosphere becomes more isolated from the surface.

The increase in temperature seen in Earth's stratosphere (as seen in Figure 1) is due to the fact that atmosphere does interact with incoming solar radiation through ozone. Ozone is produced by interaction between molecular oxygen and ultraviolet radiation in the stratosphere (Chapman, 1930), and takes over as the dominant absorber of radiation in this band. The decrease in density with height leads to an optimal level for net ultraviolet warming, and hence the temperature maximum near the *stratopause*, which provides the demarkation for the mesosphere above.

Absorption of ultraviolet radiation by stratospheric ozone protects the surface from high energy radiation. The destruction of ozone over Antarctica by halogenated compounds has had significant health impacts, in addition to damaging all life in the biosphere. As described below, it has also had significant impacts on the tropospheric circulation in the southern hemisphere.

Compositional differences

The separation in the turnover time scale between the troposphere and stratosphere leads to distinct chemical, or compositional properties of air in these two regions. Indeed, given a sample of air randomly taken from some point in the atmosphere, one can easily tell whether it came from the troposphere or the stratosphere. The troposphere is rich in water vapor and reactive organic molecules, such as carbon monoxide, that are generated by the biosphere and anthropogenic activity. Stratospheric air is

extremely dry, with an average water vapor concentration of approximate 3-5 parts per billion, and comparatively rich in ozone. Ozone is a highly reactive molecule (causing lung damage when it is formed in smog at the surface), and does not exist for long in the troposphere.

Scope and limitations of this entry

Stratospheric research, albeit only a small part of Earth System science, is a fairly mature field covering a wide range of topics. The remaining goal of this brief entry is to highlight the dynamical interaction between the stratosphere and the troposphere, with particular emphasis on the impact of the stratosphere on surface climate. In the interest of brevity, references have been kept to a minimum, focussing primarily on seminal historic papers and reviews. More detailed references can be found in the review articles listed in further readings.

The stratosphere also interacts with the troposphere through the exchange of mass and trace chemical species, such as ozone. This exchange is critical for understanding atmospheric chemistry in both the troposphere and stratosphere and has significant implications for tropospheric air quality, but will not be discussed. For further information, please see two review articles, Holton et al (1995) and Plumb (2002). The primary entry point for air into the stratosphere is through the tropics, where the boundary between the troposphere and stratosphere is less well defined. This region is known as the *tropical tropopause layer* and a review by Fuegistaler et al (2009) will provide the reader an introduction to research on this topic.

Dynamical coupling between the stratosphere and troposphere

The term "coupling" suggests interactions between independent components, and so begs the question as to whether the convenient separation of the atmosphere into layers is merited in the first place. The key dynamical distinction between the troposphere and stratosphere lies in the differences in their stratification, and the fact that moist processes (i.e. moist convection and latent heat transport) are restricted to the troposphere. The separation between the layers is partly historical, however, evolving in response to the development of weather forecasting and the availability of computational resources.

Midlatitude weather systems are associated with large scale Rossby waves, which owe their existence to gradients in the rotation, or vorticity, of the atmosphere in the vertical due to variations in the angle between the surface plain and the axis of rotation with latitude. Pioneering work by Charney and Drazin (1961) and Matsuno (1970) showed that the dominant energy containing waves in the troposphere, wavenumber roughly 4-8, so-called *synoptic scales*, cannot effectively propagate into the stratosphere due the presence of easterly winds in the summer hemisphere and strong westerly winds in the winter hemisphere. For the purposes of weather prediction, then, the stratosphere could largely be viewed as an upper boundary condition. Models thus resolved the stratosphere as parsimoniously as possible in order to focus numerical resources on the troposphere. The strong winds in the winter stratosphere also impose a stricter Courant-Friedrichs-Lewy condition on the time step of the model, although more advanced numerical techniques have alleviated this problem.

Despite the dynamical separation for weather system scale waves, larger scale Rossby waves (wavenumber 1-3, referred to as planetary scales), can penetrate into the

winter stratosphere, allowing for momentum exchange between the layers. In addition, smaller scale (on the order of 10-1000 km) gravity waves[3] also transport momentum between the layers. As computation power increased, leading to a more accurate representation of tropospheric dynamics, it became increasingly clear that a better representation of the stratosphere was necessary to fully understand and simulate surface weather and climate.

Coupling on daily to intraseasonal time scales

Weather prediction centers have found that increased representation of the stratosphere improves tropospheric forecasts. On short time scales, however, much of the gain comes from improvements to the tropospheric initial condition. This stems from better assimilation of satellite temperature measurements which project onto both the troposphere and stratosphere.

The stratosphere itself has a more prominent impact on intraseasonal time scales, due to the intrinsically longer time scales of variability in this region of the atmosphere. The gain in predictability, however is conditional, depending on the state of the stratosphere. Under normal conditions, the winter stratosphere is very cold in the polar regions, associated with a strong westerly jet, or *stratospheric polar vortex*. As first observed in the 1950s (Scherhag, 1952), this strong vortex is sometimes disturbed by planetary wave activity propagating below, leading to massive changes in temperature (up to 70 degrees C in a matter of days) and a reversal of the westerly jet, a phenomenon known as a *Sudden Stratospheric Warming*, or SSW. While the predictability of SSWs are limited by the chaotic nature of tropospheric dynamics, after an SSW the stratosphere remains in altered state for up to 2-3 months as the polar vortex slowly recovers from the top down.

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[3] Gravity waves are generated in stratified fluids, where the restoring force is the gravitational acceleration of fluid parcels, or buoyancy. They are completely distinct from relativistic gravity waves.

Baldwin and Dunkerton (2001) demonstrated the impact of these changes on the troposphere, showing that an abrupt warming of the stratosphere is followed by an equatorward shift in the tropospheric jet stream and associated storm track. An abnormally cold stratosphere is conversely associated with a poleward shift in the jet stream, although the onset of cold vortex events are not as abrupt. More significantly, the changes in the troposphere extend for up to 2-3 months on the slow time scale of the stratospheric recovery, while under normal conditions chaotic nature of tropospheric flow restricts the time scale of jet variations to approximately 10 days. The associated changes in the stratospheric jet stream and tropospheric jet shift are conveniently described by the *Northern Annular Mode*[4] (NAM) pattern of variability.

The mechanism behind this interaction is still an active area of research. It has become clear, however, that key lies in the fact that the lower stratosphere influences the formation and dissipation of synoptic scale Rossby waves, despite the fact that these waves do not penetrate far into the stratosphere.

A shift in the jet stream is associated with a large scale rearrangement of tropospheric weather patterns. In the northern hemisphere, where the stratosphere is more variable due to the stronger planetary wave activity (in short, because there are more continents), an equatorward shift in the jet stream following an SSW leads to colder, stormier weather over much of northern Europe and eastern North America. Forecast skill of temperature, precipitation, and wind anomalies at the surface is increases in seasonal forecasts following an SSW. SSWs can be further differentiated into "vortex displacements" and "vortex splits," depending on the dominant wavenumber (1 or 2, respectively) involved in the breakdown of the jet, and recent work has suggested this has an effect on the tropospheric impact of the warming.

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[4] The NAM is also known as the *Arctic Oscillation*, although the annular mode nomenclature has become more prominent.

SSWs occur approximately every other year in the northern hemisphere, although there is strong intermittency: few events were observed in the 1990's, while they have been occurring in most years in the first decades of the 21st century. In the southern hemisphere, the winter westerlies are stronger and less variable – only one SSW has ever been observed, in 2002 – but predictability may be gained around the time of the"final warming," when the stratosphere transitions to it's summer state with easterly winds. Some years this transition is accelerated by planetary wave dynamics, as in an SSW, while in other years it is gradual, associated with a slow radiative relaxation to the summer state.

Coupling on interannual time scales scales

On longer timescales, the impact of the stratosphere is often felt through a modulation of the intraseasonal coupling between the stratospheric and tropospheric jet streams. Stratospheric dynamics play an important role in internal modes of variability to the atmosphere-ocean system, such as El Niño and the Southern Oscillation (ENSO), and in the response of the climate system to "natural" forcing by the solar cycle and volcanic eruptions.

The Quasi-Biennial Oscillation (QBO) is a nearly periodic oscillation of downward propagating easterly and westerly tropical jets in the tropical stratosphere, with a period of approximately 28 months. It is perhaps the most long lived mode of variability intrinsic to the atmosphere alone. The QBO influences the surface by modulating the wave coupling between the troposphere and stratosphere in the northern hemisphere winter, altering the frequency and intensity of SSWs depending on the phase of the oscillation.

Isolating the impact of the QBO has been complicated by possible overlap with the ENSO, a coupled mode of atmosphere-ocean variability with a time scale of ap-

proximately 3-7 years. The relatively short observational record makes it difficult to untangle the signals from measurements alone, and models have only recently been able to simulate these phonomenon with reasonable accuracy. ENSO is driven by interaction between between the tropical Pacific ocean and the zonal circulation of the tropical atmosphere (the Walker Circulation). Its impact on the extratropical circulation in the Northern Hemisphere, however, is in part effected through its influence on the stratospheric polar vortex. A warm phase of ENSO is associated with stronger planetary wave propagation into the stratosphere, and hence a weaker polar vortex and equatorward shift in the tropospheric jet stream.

Further complicating the statistical separation between the impacts of ENSO and the QBO is the influence of the 11 year solar cycle, associated with changes in the number of sunspots. While the overall intensity of solar radiation varies less than 0.1% of its mean value over the cycle, the variation is stronger in the ultraviolet part of the spectrum. Ultraviolet radiation is primarily absorbed by ozone in the stratosphere, and it has been suggested that the associated changes in temperature structure alter the planetary wave propagation, along the lines of the influence of ENSO and QBO.

The role of the stratosphere in the climate response to volcanic eruptions is comparatively better understood. While volcanic aerosols are washed out of the troposphere on fairly short timescales by the hydrological cycle, sulfate particles in the stratosphere can last for 1-2 years. These particles reflect incoming solar radiation, leading to a global cooling of the surface; following Pinatubo the global surface cooled 0.1-0.2 K. The overturning circulation of the stratosphere lifts mass up into the tropical stratosphere, transporting it polewards where it descends in the extratropics. Thus only tropical eruptions have a persistent, global impact.

Sulfate aerosols warm the stratosphere, therefore modifying the planetary wave coupling. There is some evidence that net result is a strengthening of the polar vortex,

and so a poleward shift in the tropospheric jets. Hence eastern North America and northern Europe may experience warmer winters following eruptions, despite the overall cooling impact of the volcano.

The Stratosphere and Climate Change

Anthropogenic forcing has changed the stratosphere, with resulting impacts on the surface. While greenhouse gases warm the troposphere, they increase the radiative efficiency of the stratosphere, leading to a net cooling in this part of the atmosphere. The combination of a warming troposphere and cooling stratosphere leads to a rise in the tropopause, and may be one of the most identifiable signatures of global warming on the atmospheric circulation.

While greenhouse gases will have the dominant long term impact on the climate system, anthropogenic emissions of halogenated compounds, such as chlorofluorocarbons (CFCs), have had the strongest impact on the stratosphere in recent decades. Halogens have caused some destruction of ozone throughout the stratosphere, but the extremely cold temperatures of the Antarctic stratosphere in winter permit the formation of *polar stratospheric clouds*, which greatly accelerate the production of Cl and Br atoms that catalyze ozone destruction (e.g. Solomon, 1999). This led to the ozone hole, the effective destruction of all ozone throughout the middle and lower stratosphere over Antarctica. The effect of ozone loss on ultraviolet radiation was quickly appreciated, and the use of halogenated compounds to regulated and phased out under the Montreal Protocol (which came into force in 1989) and subsequent agreements. Chemistry climate models suggest that the ozone hole should recover by the end of this century, assuming the ban on halogenated compounds is observed.

It was not appreciated until the first decade of the 21st century, however, that the ozone hole also has impacted the circulation of the southern hemisphere. The loss of

ozone leads to a cooling of the austral polar vortex in springtime, and, as in response to natural increase in the strength of the vortex in the norther hemisphere, a subsequent poleward shift in the tropospheric jet stream. As reviewed by Thompson et al (2011), this shift in the jet stream has had significant impacts on precipitation across much of the Southern Hemisphere.

Stratospheric trends in water vapor also have the potential to affect the surface climate. Despite the minuscule concentration of water vapor in the stratosphere (just 3-5 parts per billion), the radiative impact of a greenhouse gases scales logarithmically, so relatively large changes in small concentrations can have an strong impact. Decadal variations in stratospheric water vapor can have an influence on surface climate comparable to decadal changes in greenhouse gas forcing, and there is evidence of a positive feedback of stratospheric water vapor on greenhouse gas forcing.

The stratosphere has also been featured prominently in the discussion of *climate engineering* (or *geoengineering*), the deliberate alteration of the Earth System to offset the consequences of greenhouse induced warming. Inspired by the natural cooling impact of volcanic aerosols, the idea is to inject hydrogen sulfide or sulfur dioxide into the stratosphere, where it will form sulfate aerosols. To date, this strategy of so-called *solar radiation management* appears to be among the most feasible and cost effective means of cooling the Earth's surface, but comes with many dangers. In particular, it does not alleviate ocean acidification and the effect is short lived – a maximum of two years – and so would require continual action ad infinitem, or until greenhouse gas concentrations were returned to safer levels. (In saying this, it is important to note that the natural time scale for carbon dioxide removal is 100,000s of years, and there are no known strategies for accelerating CO2 removal that appear feasible, given current technology.) In addition, the impact of sulfate aerosols on stratospheric ozone,

and potential regional effects due to changes in the planetary wave coupling with the troposphere, are not well understood.

Further Reading

There are a number of review papers on stratosphere-tropospheric coupling in the literature. In particular, Shepherd (2002) provides a comprehensive discussion of stratosphere-troposphere coupling, while Gerber et al (2012) highlights developments in the last decade. Andrews et al (1987) is a classic text on the dynamics of the stratosphere, and Labitzke and Loon (1999) provides a wider perspective on the stratosphere, including the history of field.

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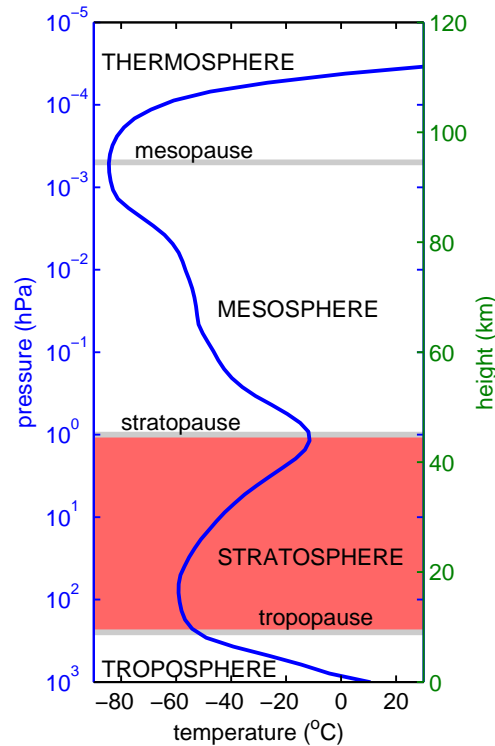
Fig. 1. The vertical temperature structure of the atmosphere. This sample profile shows the January zonal-mean temperature at 40 N from the Committee on Space Research (COSPAR) international reference atmosphere 1986 model (Cira-86). The changes in temperature gradients, and hence stratification of the atmosphere, reflect difference in the dynamical and radiative processes active in each layer. The height of the separation points (tropopause, stratopause, and mesopause) vary with latitude and season – and even on daily time scales due to dynamical variability – but are generally sharply defined in any given temperature profile.

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