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HIRDLS

HIGH RESOLUTION DYNAMICS LIMB SOUNDER

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This document describes the scientific goals of the High Resolution Dynamics Limb Sounder (HIRDLS) project and specifies the geophysical quantities that must be measured by the HIRDLS instrument in order to meet these goals.

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DOCUMENT REVISIONS

Substantive Revisions to This Document, Relative to the Previous Version

Section Number	Section Heading	Comments
1.1	Principal Scientific Objectives	added an eighth objective, corresponding to the new § 9 about aerosols and clouds
3.6	Ozone Depletion	added the section
4.3	Gravity Waves	rewrote the section to better describe the utility of HIRDLS observations in constraining gravity wave models
8.1	Overview	added “In addition, appreciable amounts of OH are thought to be produced from acetone, methyl peroxide, and formaldehyde.”
8.2	Use of HIRDLS Observations in Tropospheric Chemistry	rewrote the section to simplify and clarify the application of HIRDLS observations to questions about tropospheric chemistry
9	Improving the Understanding of Stratospheric and Tropospheric Aerosols and Clouds	added the section; changed the section numbers of sections 9 through 12 to 10 through 13
12	Basic Data Products	rewrote portions of the section and Table 1 to include information about aerosol and spectral channel extinction measurements
13	Summary	rewrote portions of the section to reflect the latest information about CFCs

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1 Introduction

Our ideas about the chemistry and dynamics of the atmosphere, particularly the middle atmosphere, have changed profoundly since the discovery (in 1985) of the rapid decline of the springtime ozone column over Antarctica. This completely unexpected phenomenon spawned many new measurements, theories, and models—and also "new chemistry"—that provide a partial explanation of the processes involved. The development of our understanding of atmospheric dynamics has been much less dramatic, but no less important. However, the details are known only by the specialists. Observational studies and theoretical developments have fundamentally changed our ideas about planetary-scale Rossby waves, wave-mean-flow interactions, quasi-two-dimensional turbulence, and diabatic circulations. These developments have far-reaching implications for our understanding of the general circulation of the middle atmosphere, the associated transport and mixing of trace constituents, and the effects of radiation and photochemistry on a wide range of spatial scales.

An important step in the learning process was the discovery that, with careful interpretation, the existing satellite data are good enough to give direct new insight into the dynamics of planetary-scale Rossby waves. This analysis demonstrated that these prominent features of the wintertime stratospheric circulation can cause *in-situ* generation of motion at scales that are too small to be resolved by existing space-based systems and are far smaller than envisaged in classical theories of the stratosphere. The process by which the small-scale motions are generated is called planetary-wave breaking. The investigation of these small-scale processes and the quantification of their interaction with the large-scale dynamics, transport, and chemistry of the middle atmosphere will be a major priority in the future. The high resolution capabilities of the HIRDLS instrument will enable it to play a crucial role in this program.

The developments that are outlined above are the driving force behind many of the requirements for the HIRDLS instrument. This document describes the scientific aims of the HIRDLS project, the quantities that need to be measured, and the required accuracy of their measurement.

1.1 Principal Scientific Objectives

Eight principal scientific objectives have been chosen as the focus of the investigations for which the HIRDLS Science Team intends to use the data that is produced by the HIRDLS instrument. The objectives, which are discussed in sections 2 to 9, are:

1. To understand the fluxes of mass and chemical constituents (including greenhouse gases and aerosols) that affect the dynamics and composition of the troposphere, stratosphere, mesosphere, and thermosphere and link these regions together. These fluxes must be determined down to smaller scales than previously observed.

2. To understand the chemical processing, transport, and small-scale irreversible mixing of trace constituents in the middle atmosphere, including the chemical and dynamical processes responsible for creating the antarctic (and perhaps arctic) ozone holes.

3. To understand the momentum, energy, and potential vorticity balances of the middle atmosphere, by extending global observations to smaller horizontal and vertical scales than has previously been possible. These small-scale processes are believed to be fundamentally important to the determination of some large-scale characteristics and are thought to cause irreversible chemical mixing.

4. To obtain climatologies of upper tropospheric, stratospheric, and mesospheric quantities, in particular, profiles of temperature, ozone, several radiatively active gases, aerosol, gravity wave activity, and cloud top heights. Seasonal, interannual, and long-term trends will be obtainable because of the five-year measurement sequence that will be provided by each Earth Observing System (EOS) instrument, combined with pre-EOS measurements and future EOS observations.

5. To provide data to validate and improve numerical models of the atmosphere, in order to gain confidence in their ability to predict climate change. These simulations are critically dependent on the treatment of horizontal and vertical scales that are much finer than those currently observed.

6. To improve tropospheric temperature and water vapor profiles and cloud top height data that are used for climate and weather forecasting, by combining high vertical resolution limb data with data from operational nadir sounders such as AIRS and AMSU. This will yield valuable data from the tropopause region and the lower stratosphere, information that would not otherwise be available.

7. To improve the understanding of tropospheric chemistry through the use of temperature and constituent retrievals that extend into the upper troposphere, under favorable conditions. The combination of these observations with observations from other EOS instruments, and with chemical models, will yield information about the oxidation capacity of the atmosphere.

8. To improve the understanding of stratospheric and tropospheric aerosols and clouds by acquiring long-term high-resolution observations of their nature and distribution. Aerosols and polar stratospheric clouds are now known to play essential roles in the depletion of ozone in the lower stratosphere, and subvisible cirrus clouds in the upper troposphere significantly impact the radiative heating and cooling of the atmosphere.

Within each of the preceding objectives, several key studies have been identified by the Science Team. The functional requirements for the HIRDLS instrument have been determined by considering the data quality that is necessary to produce useful results from these key studies.

2 Flow of Mass and Constituents through the Middle Atmosphere

The budget of stratospheric ozone is determined not only by radiative and photochemical processes, but also by transport. Transport processes of significance include the exchange of photochemically and radiatively important substances between the troposphere and the stratosphere, the bulk motion of these substances through the stratosphere, and their irreversible mixing within the stratosphere. The meteorological processes that determine the rates of troposphere-stratosphere exchange and bulk transport and mixing within the stratosphere are known to have strong variability on time scales from days to years, and these processes can create tracer variability on a wide range of time scales. An understanding of these processes is crucial not only for determining tracer budgets at any time, but also for distinguishing trace species trends from natural variability. Elucidation of the mechanisms that produce spatial or temporal variations of transport and exchange is an essential component of the study of the ozone layer.

A number of recent theoretical studies have attempted to identify simple ways of characterizing the slow, mean meridional transport of chemicals and other tracers. There are several alternative theoretical formulations (e.g., the residual circulation that is discussed in § 4) that allow this transport to be diagnostically estimated from thermodynamic considerations, given the observed temperatures and an accurate radiation scheme. An alternative approach is to use several long-lived chemical species to estimate mass transport circulations directly. SAMS measurements of the mixing ratios for CH_4 and N_2O have revealed qualitative features of the mean meridional mass transport. These species are produced at the surface and are relatively stable in the troposphere. They enter the stratosphere primarily in the tropics and are converted into other species under the influence of ultraviolet light as they move upwards. CFC 11 and CFC 12 have similar vertical profiles to CH_4 and N_2O, but with stronger gradients in the lower stratosphere. These four gases will be measured by the HIRDLS instrument and will provide vertical and meridional transport information at different heights. Most of the information that is obtained from a species corresponds to the region where its mixing ratio gradient is the largest. The chlorofluorocarbons (CFCs) are easier to interpret than CH_4 or N_2O, because the CFCs are destroyed at rates that are determined purely by photolysis, whereas the destruction rates for CH_4 and N_2O are partly determined by the abundance of other species. As tracers of tropospheric air, CFCs are also important for observing the degree of isolation of the polar vortices and the nature of the transport and intermixing down to the smallest measured scales.

Tracer exchange across the tropopause and mixing within the stratosphere involve smaller horizontal and vertical scales than those that were sampled in previous satellite experiments. The UARS instruments greatly increase the number of trace species that are sampled, but they do not improve the horizontal resolution of the observational database of meteorological parameters. The dramatic increase in horizontal resolution that is achievable with the HIRDLS instrument, combined with its excellent vertical resolution, provides an unparalleled opportunity for developing a better understanding of the transport and exchange processes. Data from the HIRDLS mission should enable us to answer a number of important questions, including:

1. What are the processes and rates for the transfer of several radiatively or chemically important species between the troposphere and the stratosphere?

2. What are the spatial and temporal distributions of these transfer processes?

3. How are substances that enter the stratosphere in the equatorial region redistributed in height, latitude, and longitude by bulk advective processes?

4. What is the role of mixing in this redistribution?

During the next few years, the theoretical work that is currently underway should make significant progress toward answering some of these questions. However, model validation will not be possible in the period prior to EOS because of the lack of observations that have the required horizontal resolution of no more than a few hundred kilometres.

3 Chemical Processing and Mixing of Trace Constituents

3.1 Overview

The stratosphere is an important component of the climate system of the earth: it controls the fate of several gases that contribute to the warming of the planet, and it contains most of the ozone that protects the biosphere from the harmful effects of solar ultraviolet radiation. Trace constituents (e.g., some greenhouse gases) are produced at the surface of the earth as a result of biospheric, oceanic, volcanic, and anthropogenic processes. If the constituents that are released at the surface react slowly with tropospheric radicals such as OH, their lifetimes are sufficiently long to allow them to penetrate into the stratosphere. Most constituents that reach the stratosphere are destroyed there by oxidation or photolytic mechanisms, leading to the formation of several fast-reacting radicals. These radicals initiate complex chemical mechanisms that affect the distribution of most trace gases, including ozone. Ozone is produced in the stratosphere as a result of the photodissociation of molecular oxygen by solar ultraviolet radiation. It is destroyed primarily by catalytic reactions that involve hydrogen, nitrogen, and halogen radicals, which are themselves produced by the decomposition of long-lived (greenhouse) gases. The chemical lifetime of most trace gases is a strong function of height and can also depend significantly on latitude. Obtaining a global picture of chemistry and dynamics (transport) requires the simultaneous measurement of different species. These species must be chosen so that their chemical lifetimes are comparable to their transport lifetimes in different (preferably overlapping) regions of the atmosphere. The set of trace gases that will be measured by the HIRDLS instrument was chosen because of this property, together with additional constraints that result from the requirements of simultaneous and co-located measurements for chemical balances.

3.2 Interaction of Transport and Chemistry

The fate of trace gases in the atmosphere is largely determined by their chemical lifetimes. In regions where its chemical lifetime is long, a species can be transported over great distances before being significantly affected by chemical processes. A species tends to exhibit weak concentration gradients within such long-lifetime regions, unless there are rapid transport processes from regions where its chemical lifetime is short (e.g., a species that is cycling in and out of the polar night as it circulates around a polar vortex). Therefore, the distribution of long-lived species does not generally provide much information about the transport properties of the atmosphere. Fast-reacting (short-lived) species are affected primarily by the local chemical and photochemical environment. They are relatively insensitive to transport processes and cannot be used to deduce transport information. Quantitative observations of these species are useful for understanding the chemical balances that are involved and generally require simultaneous measurements of two or more constituents. The most useful information on transport is obtainable when the rate of formation or destruction of a chemical species is somewhat longer than, but still comparable to, the rate at which it is transported. Under these conditions, substantial gradients in the species concentration are observed, but the amount of the species is still roughly conserved over short periods. Knowledge of the concentrations of other species is not a prerequisite to understanding the local budgets and determining transport rates. The case of ozone is illustrative of these different regimes. The chemical lifetime of ozone in the upper atmosphere is less than a day, and its distribution is determined primarily by the concentration of chemical radicals, solar irradiance, and the local temperature. However, these parameters are not independent of the dynamics of the stratosphere, so transport does act indirectly on ozone in this region. On the other hand, the chemical lifetime of ozone near the tropopause is longer than a year, and its distribution is directly affected by the prevailing winds (advection), by different types of waves, and by turbulent mixing.

Strong horizontal gradients in the chemical composition can occur in several regions of the atmosphere. The most obvious are: the solar terminator (for species with strong diurnal variation, such as NO_2 or O_3 in the mesosphere) and the edge of the polar vortex (where airborne measurements have revealed large composition changes over distances of 100 km to 200 km). Limb sounders have inherently limited spatial resolution along their view direction. Hence, the ability to orient the line of sight perpendicular to the species gradients will be important in some situations, particularly at the edge of the polar vortex. If this is done, the resolution is limited primarily by the width of the field of view and the duration of the observation. Alternatively, the special observing modes will permit the tomographic deconvolution of the measurements along the line of sight.

3.3 Chemical Balances

In regions where two or more of the species that will be observed by the HIRDLS instrument have very short chemical lifetimes, it will be possible to deduce the concentrations of additional species from the chemical balances that are associated with the observed concentrations. For example, the OH concentration has been previously derived from the HNO_3 / NO_2 ratio that was measured by the LIMS instrument, and it has been deduced by using a 2-D model combined with the SAMS and LIMS observations of temperature, O_3, H_2O, CH_4, NO_2, and HNO_3.

3.4 Planetary-Wave Breaking

Planetary-scale Rossby waves of large amplitude are normally present during the winter. They are an important vertical-coupling mechanism between the troposphere, stratosphere, and mesosphere. Planetary-wave breaking causes rapid and irreversible deformation of the material contours (i.e., mixing), in contrast to the reversible undulation of these contours that is described by standard linear wave theory. It is also thought to generate small-scale motions *in situ*. Isentropic potential vorticity (IPV) maps that are based on SSU and LIMS data show that the winter mid-stratosphere is divided into two types of regions: one within which the IPV contour deformations appear to be approximately reversible and wave propagation is important, and another (stratospheric surf zones) within which wave breaking appears to be a significant phenomenon. Relative to the current limits of observational resolution, these surf zones are two-dimensionally turbulent: the mixing of tracers in the surf zones is much more rapid than in the adjacent wave propagation regions, such as the main circumpolar vortex. The two types of regions are closely juxtaposed, resulting in extreme inhomogeneity that must be taken into account in quantitative treatments of the effects of dynamics and transport on constituents, and in the development of better parameterizations of small-scale processes. The information that is needed for these analyses can only be acquired by an observing system that has much better vertical and horizontal resolution than previous systems. The HIRDLS instrument will provide crucial fine resolution data against which to validate the parameterizations of small-scale processes.

3.5 Layering

Vertical profiles of minor constituents in the lower stratosphere frequently display pronounced layering, specifically, regions with a uniform mixing ratio that are up to 2 km deep, separated by very sharp concentration gradients. This layering has been observed in ozonesonde profiles at middle and high latitudes, in lidar profiles of volcanic aerosols, and in upper tropospheric humidity profiles. The origin and morphology of the layering are poorly understood, but it appears to extend horizontally over distances of at least several hundred kilometres. Very sharp concentration gradients can only persist if vertical mixing is suppressed. A better understanding of the properties of these layers is needed to improve the modeling of vertical transports in the lower stratosphere. Combined with ground-based measurements, the HIRDLS instrument will offer a unique opportunity for a systematic study of stratospheric layering. Such persistent inhomogeneity demonstrates the need for fine vertical resolution, since low resolution measurements would suggest that the constituents are well mixed and thereby imply quite different chemical reaction and mixing rates.

3.6 Ozone Depletion

It is well known that heterogeneous chemical reactions on the surfaces of aerosols, primarily polar stratospheric clouds (PSCs), lead to ozone depletion in the Antarctic and the Arctic. In fact, unprecedented ozone loss has been observed at high northern latitudes in recent years, especially in March. This is an issue of considerable interest because of higher population densities in the Northern Hemisphere, compared to the Southern Hemisphere. However, polar ozone depletion is typically underestimated (by as much as 50 %) by global three-dimensional chemical transport models, when compared to observed ozone loss. One possible source of the discrepancy is an improper accounting of the heterogeneous chemistry at times and locations where the occurrence of PSCs is sporadic or localized, and thus more difficult to include in models which have limited temporal and spatial resolution. The high vertical, horizontal, and temporal resolution of HIRDLS observations, as well as their global coverage, will enable comprehensive investigations of the small-scale temporal and spatial variations in PSC compositions and surface
areas, and their corresponding effects on ozone loss in the polar regions.

4 Momentum, Energy, and Potential Vorticity Balances

4.1 Overview

The zonal mean angular momentum balance and the residual mean circulation are intimately linked. In addition, the residual mean circulation is usually a very good approximation to the transport circulation. The forcing of the zonal mean angular momentum by Eliassen-Palm (EP) flux divergence is balanced by advection of angular momentum, by the residual mean circulation, and by the angular momentum tendency. In general, the distribution of zonal mean angular momentum that results from this balance varies vertically (i.e., there is vertical shear of the zonal wind), and these variations are geostrophically balanced by horizontal temperature variations.

For the zonal mean wind, geostrophic balance is approximately valid, even at equatorial latitudes in the middle atmosphere. The resulting variations in temperature, together with the distribution of radiatively active gases and the solar flux, determine the distribution of diabatic heating and cooling. This information can then be used to derive the residual mean circulation. Thus, both the zonal mean flow and the residual mean circulation are related to the distribution of the sources and sinks of momentum and sensible heat that are associated with the wave and eddy fluxes, since these fluxes combine to form the EP flux divergence.

The zonal mean flow and the residual mean circulation are coupled in another way, as well. The EP flux is primarily caused by propagating Rossby, gravity, and equatorial waves, and the propagation of each of these wave types is strongly regulated by the background wind field, in particular, by the zonal mean wind. Thus, the zonal wind distribution is driven by the distribution of the EP flux divergence, but it also controls the distribution of this driver. Gravity waves dominate the EP flux divergence in the mesosphere, but planetary waves appear to account for the bulk of the wave driving that is required to maintain the observed zonal momentum balance of the winter stratosphere. Nevertheless, there are indications that gravity waves play a significant role in the upper stratosphere.

The relative roles of these two types of waves in most of the middle atmosphere and the possible role of synoptic-scale eddies are yet to be determined conclusively. Observations with high resolution, global coverage, and long duration are required to answer the following questions:

1. What are the important processes that determine the large-scale circulation of the middle atmosphere?

2. How does the relative importance of these processes change as a function of location and season?

3. What are the mechanisms by which disturbances of various kinds (planetary waves, gravity waves, etc.) interact with each other and with the background flow?

The internal dynamics of this system is sufficiently complex that, even if other factors are ignored, the flow has the ability to exhibit a rich spectrum of variability. This complexity is evidenced in the high level of interannual variability of the stratosphere. A fundamental research goal in the study of stratospheric dynamics is to obtain a quantitative understanding of the behavior of this complex system, including a knowledge of its interannual variability that is sufficient to allow reliable predictions of system behavior under perturbed conditions (e.g., under conditions in which the distributions of the concentrations of CO_2, O_3, and/or H_2O are varied from their present values, the aerosol concentration in the stratosphere is highly perturbed, or the climatology of the wave flux that enters the stratosphere from below is altered).

The diagnostic information that is necessary for the development of this understanding includes the following:

1. detailed distributions of the zonal wind field, including seasonal and interannual variations;

2. distributions of the residual mean circulation (which can be deduced from a detailed knowledge of the temperature field), radiatively active trace gases (particularly CO_2, O_3, and H_2O), and aerosols, with particular emphasis on seasonal and interannual variations; and

3. distributions of the wave and eddy fields on all scales that contribute to the EP flux divergence and its seasonal and interannual variability.

This last piece of information is by far the most troublesome factor, particularly since there is good reason to believe that the waves and eddies that vary on relatively small temporal and spatial scales are substantial contributors to the total EP flux divergence, and since there is as yet no means for obtaining a global assessment of the structure of waves and eddies at synoptic or smaller spatial scales in the middle atmosphere. By providing the capability to observe stratospheric waves at much smaller scales than previously possible, and to do this over many years, the HIRDLS instrument will greatly improve our understanding of waves, eddies, and their interannual variability. Specialized viewing modes will make it possible to observe the same region of the atmosphere on successive orbits. The resulting data—with horizontal resolution as fine as 100 km, temporal resolution of one orbital period ($\approx$ 100 min), and 1 km vertical resolution—will complement the continuous, but local, ground-based observations.

4.2 Potential Vorticity as a Diagnostic Tool

A significant recent development in atmospheric physics is the increased use of Rossby-Ertel potential vorticity (PV) as a diagnostic tool. PV is materially conserved in frictionless adiabatic flow, and it controls the evolution of most of the large-scale motion. PV is conveniently depicted by maps on isentropic surfaces (i.e., IPV maps), revealing information about large-scale air parcel motions. The connection between dynamics and air parcel motions can thus be quantified, providing an almost complete view of the dynamics. The use of IPV maps has already illuminated many atmospheric processes and clarified their connections with fundamental theoretical concepts. However, existing and currently planned satellite measurements (e.g., from SSU, LIMS, SAMS, ISAMS, CLAES, MLS, AIRS, and AMSU) have limited vertical or horizontal resolution, resulting in global IPV maps that are seriously distorted at scales of hundreds of kilometres.

A major challenge in the future will be to combine observations, data processing, and numerical modeling so that PV can be determined simultaneously with the distributions of ozone and other chemical constituents. This should provide the best possible observational estimates of PV fields and their time evolution, consistent with both chemical and dynamical data. In principle, such simultaneous retrieval techniques can greatly improve the utilization of satellite data. (They should become feasible during the coming decade, as a result of advances in computer technology.) The HIRDLS instrument, together with the associated theoretical and modeling work, will provide the relevant dynamical and chemical data at far better spatial resolution than previous instruments; so, it is expected to make a key contribution in this regard.

4.3 Gravity Waves

Internal gravity waves are believed to play a crucial role in determining the large-scale dynamical and chemical structure of most of the middle atmosphere. This is a result of their ability to transfer momentum from the regions where they are generated (e.g., the troposphere) to the regions where they are dissipated (e.g., the middle atmosphere). Middle atmosphere general circulation models need realistic constraints on the parameterization of gravity waves, because the waves have such a profound effect on the results of the models. Information about the spatial distribution and temporal variations of the sources of gravity waves in the lower atmosphere is most crucially needed.

Naturally occurring gravity waves populate a broad spectrum of wavelengths, phase speeds, and propagation directions. Information about the details of the shape and amplitude of the gravity wave spectrum is needed to parameterize the interaction between the waves and the background atmosphere. Each observation technique is limited to a portion of the gravity wave spectrum. Ground-based observations are further limited in horizontal coverage because of the small number of sites around the world. The HIRDLS instrument has the capability to observe a broader range of vertical wavelengths than any previous satellite instrument. Hence, it can provide unprecedented information about the global distribution and spectrum of waves in the middle atmosphere. The HIRDLS instrument can also observe horizontal wavelengths that span all of the scales of interest (> 10 km) by using special observing modes at low altitudes, close to the wave source heights where global data is most needed. These measurements will greatly add to our knowledge of the occurrence and global effects of gravity waves in the stratosphere and mesosphere.

4.4 Tropical Dynamics

The interacting linkage between waves and eddies, the zonal mean flow, and the residual mean circulation are more spectacularly realized in the tropical stratosphere than anywhere else. Both the semiannual and quasi-biennial oscillations (SAO and QBO, respectively) of the zonal wind are driven by equatorial waves whose distributions and properties are believed to be determined largely by the distribution of the zonal mean wind, and by the forcing from the tropical troposphere. Both cycles are associated with substantial contributions to the residual mean circulation, which in turn makes a significant contribution to the evolution of trace species concentrations. Furthermore, at least one of these oscillations (viz., the QBO), and possibly both, are implicated in the interannual variations of circulation and trace species concentrations that occur outside of the tropics.

5 Climatologies, Seasonal and Interannual Variability, and Long-Term Trends

One of the concerns that is a motivation for the EOS program is the perception that the terrestrial environment, particularly the atmosphere, is changing in ways that we do not understand. Furthermore, many of these changes appear to be the inadvertent results of human activity. Among the changes that have been observed in the troposphere are increases in the concentrations of CO_2, CH_4, N_2O, CFCs, and possibly O_3. These gases are all greenhouse gases; that is, they are gases that are projected to cause increases in the surface temperature of the earth and decreases in stratospheric temperatures. In addition, model calculations suggest that they will promote increases in the stratospheric concentrations of active chlorine, nitrogen, and hydrogen species, with subsequent reductions in the amount of ozone. We do not know what all of the consequences of these and other changes will be; it has rightly been said that humanity is engaged in an enormous geophysical experiment, the results of which we cannot yet predict with any accuracy.

Such long-term changes are difficult to detect in a background of large natural variability, such as regular seasonal, annual, and eleven-year solar cycle changes. Interference from irregular interannual variability and the QBO are even more difficult to remove. In addition, there are indications that some of the phenomena are linked to the combined effects of the solar cycle and the QBO. Thus, in order to detect small trends that result from human activities, and to understand their causes, stable measurements of many key variables must be made over long periods of time. A good knowledge of the trends in the temperature and atmospheric constituent concentrations has proven to be extremely difficult to acquire, primarily because of past changes in instrumental technique that mask changes that are relatively slow. However, an additional contributing factor is that previous instruments were not designed to measure trends, until very recently.

A data set that is based on five years of HIRDLS measurements will provide climatologies and delineate seasonal and interannual variability. Flights of additional HIRDLS instruments, spanning the planned fifteen year duration of the EOS program, have also been discussed. These instruments would provide fifteen years of uninterrupted measurements with virtually identical characteristics, and with overlap between the operating periods, specifically with the intention of trend measurement. This will enable:

1. more accurate characterization of the current climatology, for use as a benchmark against which to compare future measurements, and

2. temperature and constituent concentration trend measurements within the EOS time frame, with much greater accuracy than any previous system, with discrimination between the different scales of temporal variability, and with no geographical or seasonal biases.

Several of the methods that have been proposed for trend measurements have severe disadvantages. Space-borne ultraviolet instruments suffer long-term drifts in their calibration standards and do not function in the polar night. Vertical sounders, such as the SBUV instrument, have poor vertical resolution, do not observe the lower stratosphere, and measure only a single species. Solar occultation instruments give very poor geographical coverage, and the coverage varies systematically with the seasons, which may cause biased or spurious trends. Ground-based systems have large sampling errors, even for the densest practical network. These errors introduce large uncertainties into the trend measurements because of the horizontal shifts in the distribution patterns. Infrared nadir sounders can measure trends in the temperature (but not concentrations) with good long-term stability; however, the vertical resolution is poor.

The most reliable trend estimates will probably be obtained by combining HIRDLS measurements (which will be a high spatial resolution, uniformly weighted product) with corroborative ground-based measurements. In addition, it should be possible to deduce trends by referring to the measurements that were made by earlier instruments, namely, those on the Nimbus satellites, UARS, and the NOAA operational series.

6 Validation and Improvement of Numerical Models of the Atmosphere

6.1 Overview

Numerical models of the dynamics and chemistry of the stratosphere are important for testing our understanding of the physical and chemical characteristics of the stratosphere, and for predicting its future evolution. If we cannot construct mathematical models and solve them numerically to produce the observed characteristics of the stratosphere, then it is likely that some of the important aspects of the system are not understood. This is, in fact, true today, and it does not inspire great confidence in our ability to predict the future evolution of the stratosphere. Numerical models are continually being improved, but there are limits to what can be achieved without adequate data to validate the model simulations. Both the horizontal and the vertical resolution of the numerical models is typically greater than the corresponding resolution of the data that is available to validate the simulations. Therefore, only the gross characteristics of the simulations can be compared to observations. The behavior of many of the important processes that control the development of the simulations cannot be validated, because they occur at scales that are finer than those of current observations. The HIRDLS instrument will provide data about dynamical fields at a much higher resolution than is currently available, and it will also provide simultaneous observations of several chemical constituents, information that is needed to validate chemical transport models.

6.2 Verifying Small Scales in Simulations

Numerical models with fine resolution exhibit considerable dynamical and tracer activity on small scales, associated with gravity waves and breaking planetary waves. There are no fine resolution measurements with which to validate such models, even qualitatively (with the possible exception of TOMS total ozone fields). Successful validation over large scales, using coarse measurement fields, gives some confidence that the models function correctly, implying that the small-scale processes may also be adequately represented. However, if there is any disagreement between the models and the observations, low resolution observations provide very little information about the nature of the deficiencies in high resolution models. The validation of such models is essential to the reliable use of their predictions about climate change.

6.3 Data Assimilation

Specialized modeling techniques will play an important part in the exploitation of the data. Four-dimensional data assimilation (including adjoint/variational extensions) is being used operationally for tropospheric global analysis by several forecast centers. This process merges asynchronous data of different types, without the need to ascribe them to standard measurement times, effectively using a numerical forecasting model to interpolate in time and space. This is seen as the only way to fully exploit satellite data, particularly those data on a fine spatial scale, because the fields may change substantially between consecutive measurements, and a variety of related measurements (such as temperature, mixing ratios of different tracers, and geopotential height information) need to be combined. Four-dimensional data assimilation is being used by the British Meteorological Office to analyze middle atmosphere data from UARS. By the time of the first Polar Platform, the modeling community should be well equipped to operationally undertake such a task at the spatial resolution of the HIRDLS data.

7 Use of HIRDLS Data to Improve Tropospheric Sounding

7.1 Overview

Many areas of the study of Global Change have a critical need for accurate measurements of the tropospheric state. This need is most well defined in the area of weather prediction, where recent assessments have called for temperature measurements with 1 K accuracy and 1 km vertical resolution. Similar requirements for improvements in the global observation of water vapor are also needed. Meeting these requirements will produce major advances in the study of the hydrological cycle and atmospheric circulation, and in climate modeling and analysis. Concurrent with the EOS program, the Advanced Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) are being developed to improve the capability of sounding the troposphere. AIRS, in particular, will have many more channels than HIRS, the present operational temperature sounder. Simulations suggest that such an instrument should provide significant improvements in the accuracy and resolution of the measurements, but it will not meet the previously stated requirements at all altitudes, especially in the upper troposphere. However, the joint use of HIRDLS and AIRS/AMSU data may produce significantly improved retrievals.

7.2 Combined Use of HIRDLS and AIRS/AMSU Data

Simulations that were performed at the University of Wisconsin show that, for interferometric instruments (which have a set of weighting functions that are similar to those of AIRS), the expected vertical resolution increases from 1 km at the surface to 3.5 km at 100 mbar, and it becomes even larger at higher altitudes. This is possibly the result of the increased distance from the lower boundary. Nadir sounders typically have larger errors near the tropopause than lower in the troposphere, presumably because the temperature is lowest there. The simulations that are presented in a recent NOAA technical report show errors for HIS simulations of (0.5 to 1) K near 100 mbar.

In contrast, a limb sounder with a narrow field of view, low noise levels, and suitably chosen channel passbands is capable of determining temperatures and water vapor concentrations accurately and precisely at the tropopause, and into the troposphere if clouds permit. For instance, HIRDLS simulations yield a temperature precision of about 0.25 K in the lower stratosphere and upper troposphere. The accuracy depends upon a number of factors, but it is expected to be 1 K or better. Systematic biases between nadir and a limb sounding are not important, because they can be removed fairly easily. Therefore, the two measurement techniques are complementary: a nadir sounder acquires data all of the way down to the surface, but it tends to have larger errors and generally lower vertical resolution than a limb sounder; yet, a limb sounder cannot acquire measurements down to the surface, but it regularly sounds the lower stratosphere and often the upper troposphere with inherently high vertical resolution and high precision.

In a retrieval scheme, the limb-sounding data can be used to constrain the nadir solution in the tropopause region, and down as far as possible into the troposphere. This constraint forces the retrieval to make the best use of the nadir sounder radiances, giving better retrievals to lower levels, possibly all of the way to the surface. Simulations of retrievals with limb-sounding data, in combination with nadir-sounding data (using instrument characteristics like those of HIRDLS, AIRS, and AMSU), have shown the expected improvements in the temperature profile. These simulations will be extended to water vapor. The benefits, in terms of improved knowledge of the structure and thermodynamic variables in the troposphere, are potentially very significant.

8 Improving the Understanding of Upper Tropospheric Chemistry

8.1 Overview

The chemistry of the troposphere is now recognized as an important component of the natural system of the earth as a whole. Some trace gases, such as CH_4, N_2O, isoprenes, and terpenes are produced by natural biospheric processes and released into the atmosphere. In addition, the composition of the troposphere is subject to perturbation by human activities, such as the release of gases as industrial wastes or changing agricultural practices. The fate of a compound depends upon its chemical lifetime, the characteristic mean time until it is chemically destroyed. The chemical lifetime is critically dependent on the concentration of oxidizing species (especially the OH radical) and the rates of the reactions with them. Compounds with long chemical lifetimes (e.g., CH_4, N_2O, CFC 11 and CFC 12) have tropospheric lifetimes that are long enough to allow them to be transported into the stratosphere, where they are eventually destroyed.

The OH radical generally destroys the more reactive species, thereby cleaning the atmosphere of compounds with relatively short lifetimes. For instance, isoprene and many non-methane hydrocarbons are rapidly destroyed by reacting with OH. The replacements for industrial CFCs are also expected to be removed from the troposphere by OH, before they can reach the stratosphere. The OH radical is produced by the reaction of H_2O with electronically excited atomic oxygen, $O(^1D)$. That is,

$$H_2O + O(^1D) \rightarrow 2OH. \tag{8.1}$$

In addition, appreciable amounts of OH are thought to be produced from acetone, methyl peroxide, and formaldehyde. A variety of rapid reactions then interconvert OH, H, and HO_2;

hence, these species can be thought of as a single family, designated by the term "odd hydrogen". The loss processes for odd hydrogen are complex. One of the primary loss mechanisms in the troposphere is the conversion of HO_2 to H_2O_2, namely,

$$2HO_2 + M \rightarrow H_2O_2 + O_2 + M, \tag{8.2}$$

followed by rainout. Reactions of OH and HO_2 with peroxy radicals are also very important. The primary destruction reaction for OH (but not odd hydrogen, however) is the reaction with CO. Specifically,

$$CO + OH \rightarrow CO_2 + H. \tag{8.3}$$

Any change in the tropospheric oxidation capacity, especially in the concentration of OH, will have far-reaching effects on the stratosphere, as well as the troposphere. For this reason, the oxidation capacity of the troposphere is one of the primary concerns of the Global Tropospheric Chemistry Program of the U.S. National Science Foundation.

8.2 Use of HIRDLS Observations in Tropospheric Chemistry

Because of the opacity of clouds and dense aerosols, HIRDLS observations will not always extend into the troposphere. However, other limb-scanning instruments have shown that the observations will extend into the troposphere a reasonable fraction of the time. The HIRDLS channels and retrieval scheme are designed to permit the temperature and the concentration of several species to be determined down to 5 km in altitude, under clear conditions. Some of the potential applications of these observations are outlined below.

The HIRDLS measurements of CH_4 and N_2O in the upper troposphere will provide direct evidence of the extent of the variations of their concentrations in the upper troposphere. Where there is vigorous vertical mixing, this information should be representative of the entire free troposphere (i.e., down to the boundary layer). Similarly, such measurements may help to determine the species transport by tropospheric convection.

More significantly, HIRDLS observations will allow researchers to estimate a lower bound on the tropospheric concentration of OH, since its possible production from acetone, methyl peroxide, and formaldehyde is not included. The chemistry of the hydrogen radicals in the stratosphere has been extensively studied, using calculations based on satellite data and a limited number of direct measurements. It is possible to derive the radical concentration, because the measured species are in a steady state.

The HIRDLS measurements in the upper troposphere will provide the opportunity to extend such estimates into a different part of the atmosphere, especially when the measurements are combined with the CO data from MOPITT and TES. These estimates can be compared with *in-situ* aircraft measurements of OH. It may then be possible to see differences which will point to the importance of the additional sources.

Perhaps more importantly, it will be possible to combine HIRDLS observations with those from other instruments (e.g., TES and MLS) in a chemical data assimilation scheme. Although the OH in the upper troposphere and lower stratosphere is not expected to be measured directly, there should be enough measurements to significantly constrain the chemistry. This approach has tremendous potential to provide preliminary global satellite data about some vital aspects of tropospheric chemistry.

9 Improved Understanding of Stratospheric and Tropospheric Aerosols and Clouds

Aerosols and clouds produce an interfering signal that must be removed in order to properly retrieve the atmospheric chemical composition that is implied by the HIRDLS data. However, aerosols and clouds are of great interest in their own right.

Ambient stratospheric aerosols are composed mainly of sulfuric acid that is generated from sulfur-containing gases which are produced by natural and anthropogenic processes in the troposphere. These aerosols have chemically reactive surfaces. During the past few years it has been discovered that the major pathways which lead to ozone loss in the lower stratosphere involve reactions on the surfaces of these aerosols. In order to quantitatively understand the ongoing changes in ozone levels, and to predict future ozone levels, it is essential to monitor the aerosol surface area, and to determine the processes that control the surface area. The HIRDLS instrument will contribute to this investigation by obtaining long-term global measurements of the aerosols. The infrared aerosol extinction is directly proportional to the aerosol mass for such relatively small particles. From measurements at several wavelengths, and from correlative data, the particle size and composition can be determined. By observing the temporal and geographic distributions of the aerosols, insight into their microphysics can be obtained. Aerosols are also a useful dynamical tracer.

Large explosive volcanic eruptions can inject significant amounts of sulfur dioxide and volcanic ash into the stratosphere. The volcanic ash falls out of the stratosphere relatively quickly, but the sulfur dioxide is converted to sulfuric acid which condenses to form small long-lasting aerosols. Although very large eruptions (such as that of Mt. Pinatubo in 1991) have only occurred about once per decade during the past thirty years, there are many smaller eruptions that inject material into the lower stratosphere. These volcanic clouds affect ozone by providing surfaces for reactions, they alter the radiation balance of the earth and consequently the surface climate, and they may alter the radiation balance of the stratosphere enough to affect the dynamics and temperature of the stratosphere. Volcanic clouds start as localized injections into the stratosphere. Therefore, by following their dispersion, much can be learned about stratospheric dynamics. Since the clouds usually persist for only a few years, they represent a short-term perturbation to atmospheric chemistry and climate. The perturbation can reveal atmospheric responses to external forcing that are difficult to detect from more slowly varying forcing mechanisms, such as the injection of greenhouse gases. The HIRDLS instrument will be able to observe the clouds from volcanic eruptions. The characteristics of the dispersal of these clouds will yield information about stratospheric dynamics. By measuring the properties of clouds, such as location, particle mass, and perhaps particle size, the HIRDLS instrument will provide data that is essential to modelers of atmospheric chemistry, stratospheric dynamics, and climate.

Polar stratospheric clouds form during the winter in both polar regions. These clouds contain ice, liquid water, nitric acid, and sulfuric acid, in varying proportions. At present, the composition of these clouds is not precisely known. Some clouds appear to contain liquid particles; others, solid particles. These clouds provide surfaces on which chemical reactions occur that are essential to the formation of the ozone hole. In addition, they remove nitrogen oxides from the vapor phase; and by sedimentation, the clouds may remove nitrogen and water from the stratosphere. The HIRDLS instrument will obtain relatively high spatial resolution data about the extent of these clouds. By correlating observations of the clouds with observations of gaseous nitric acid and water, we may be able to better determine the physical and chemical processes that lead to the formation of these clouds.

Several different types of aerosols and clouds are found in the upper troposphere. The various types of cirrus clouds may significantly affect HIRDLS observations . Cirrus clouds are composed of ice; and depending on their mode of formation, they may be optically thin or optically thick. The HIRDLS instrument will only be able to register the presence of optically thick clouds. However, there is an important class of cirrus, known as subvisible cirrus (because they are not apparent to the naked eye), which the HIRDLS instrument may be able to probe in detail. These clouds are known to have a significant impact on the infrared radiation that leaves the atmosphere toward space. They may also affect the heating rates near the tropical tropopause, inducing exchange between the troposphere and the stratosphere. These clouds are not well studied, because they tend to be too high in the atmosphere to study them with most available research aircraft. From lidar and satellite observations, we know that they cover a significant portion of the tropics, often extending for thousands of kilometres as cloud sheets that are a few hundred metres thick. The HIRDLS instrument will provide data about the frequency of the occurrence of such clouds. It may also be able to correlate the locations of the clouds with the height of the tropopause, and with the distribution of water vapor, providing information about the mechanisms and rates of exchange of moist air between the troposphere and the stratosphere.

10 Requirements for Measurement Advances

10.1 Observing the Lower Stratosphere and the Upper Troposphere

Previous limb sounders, including those on UARS, were designed to give optimal results in the middle and upper stratosphere. In some cases, they used a limited number of channels; so, spectral passband selection was an inevitable compromise. The lower stratosphere and upper troposphere are the critical region through which trace gases (notably those reduced gases that are produced by biogenic processes at the surface) are transported into the stratosphere, and their oxidized products are returned to the troposphere. This region also couples the dynamics of the lower troposphere to the middle stratosphere. In addition, the chemistry within this portion of the atmosphere is crucial. Figure 10.1 shows the changes that ozone underwent over Antarctica during the springtime of 1987. Most of the change occurred below about 20 km, with a large portion of it below 15 km. If measurements were made only above this region, an essential part of ozone chemistry would be missed. It is difficult to measure the lowest portion of the atmosphere with limb sounding, because the limb path is opaque over most of the spectrum and contaminated with aerosol; yet, only limb sounding can achieve adequate vertical resolution.

One of the major goals for the HIRDLS instrument is to extend the observing techniques downward to the lower stratosphere, through the tropopause, and into the upper troposphere (i.e., down to 8 km or less, in the polar regions). Several channels have been included specifically to detect the presence and properties of aerosols, allowing their effects to be removed during the retrieval process. By removing aerosol effects, the retrievals will extend reliably down through the lower stratosphere, the tropopause region, and into the upper troposphere. Considerable effort will be put into the retrieval algorithms, in order to obtain the best possible data down to the cloud tops.

10.2 High and Consistent Spatial Resolution

Recent theoretical advances have shown that the large-scale planetary waves in the wintertime stratospheric circulation can cause *in-situ* generation of scales of motion that are too small to be resolved by existing space-based systems, and far smaller than envisaged in classical theories of the stratosphere. The process by which the small-scale motions are generated is called planetary-wave breaking. A major priority in the future will be to investigate these small-scale processes and quantify their interaction with the large-scale dynamics, transport, and chemistry of the middle atmosphere. This fact is exemplified by Figure 10.2a, which shows a simulated nitrous oxide field, produced by a high resolution general circulation model. The field is dominated by structure at the finest resolution of the model. If the field is smoothed (see Figure 10.2b), the familiar large-scale structures are more apparent, but even they have very sharp features, such as the trough over Europe.

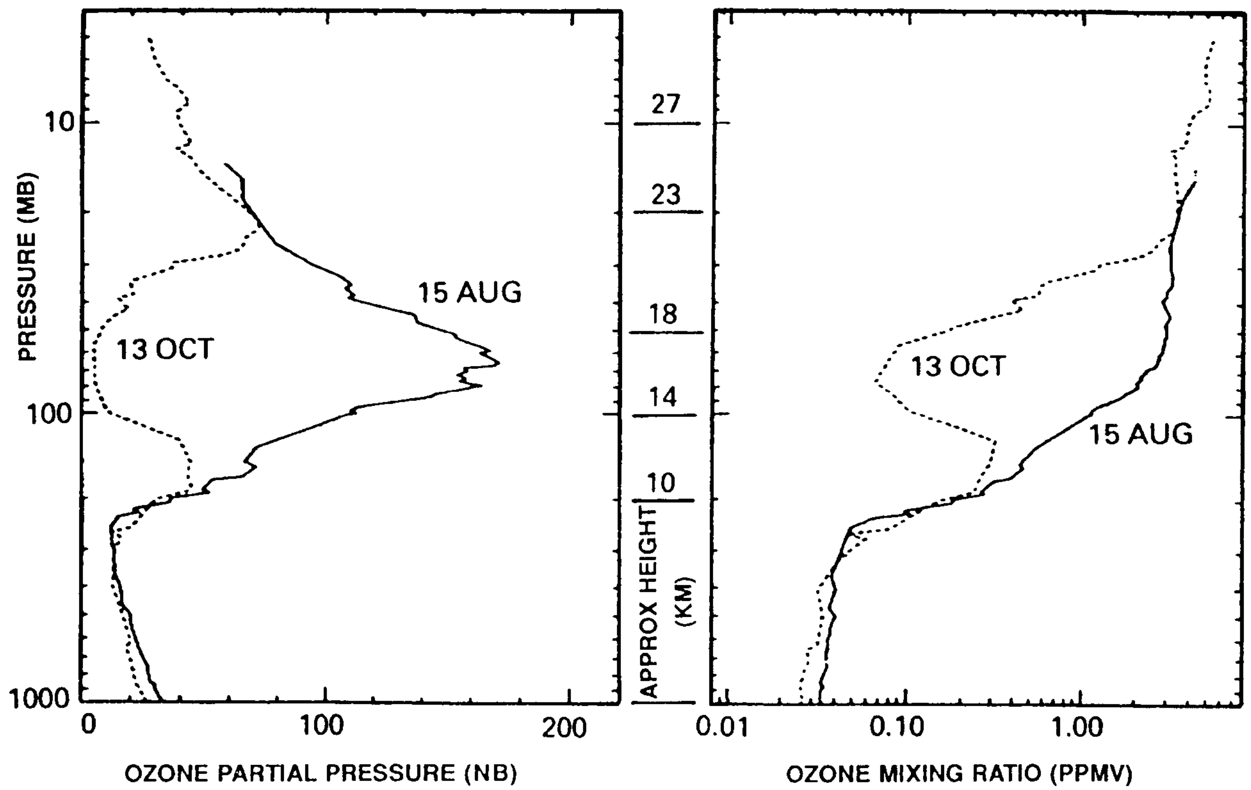

Figure 10.1—Ozone depletion during the antarctic spring of 1987 over Halley Bay (76°S).

Figure 10.3 shows the vertical and horizontal scales over which the current atmospheric numerical models operate, a few degrees horizontally and (1 to 2) km vertically. The figure also shows three theoretical curves that indicate the expected values for dynamical disturbances at various latitudes. For circulations outside of the equatorial region, quasi-geostrophic theory indicates that the ratio of the vertical resolution to the horizontal resolution of the flow structures should be roughly f / N (i.e., the Coriolis parameter divided by the buoyancy frequency). This ratio is approximately 1 / 100 for the stratosphere at middle latitudes, and it is similar to the ratio of the vertical to the horizontal data resolution of the HIRDLS instrument.

Observation systems and numerical models should ideally have resolutions that are dynamically consistent. Resources are wasted if, after applying the necessary scaling, resolution in one dimension is substantially better than in another. Figure 10.4 shows the resolutions that were obtained by previous middle atmosphere sounders. (Note that the axes are greatly expanded compared to the previous figure.) For the limb sounders, the vertical resolution is the nominal vertical field of view, and the horizontal resolution is the largest profile spacing (generally the interorbital gap). All of the previous satellite measurements of the middle atmosphere have either had fundamental inconsistencies in their resolution, or the resolutions have been relatively poor. Nadir sounders (e.g., SSU) can provide relatively high horizontal resolution through cross-track scanning, but they have limited vertical resolution (10 km at best) because of the depth of the weighting functions in the retrievals. Limb scanners (e.g., LIMS, CLAES, ISAMS, and MLS) provide much better vertical resolution (≈ 3 km prior to HIRDLS), but their horizontal resolution (at least longitudinally) has been limited to six zonal waves (≈ 2000 km) by their inability to perform cross-track scanning.

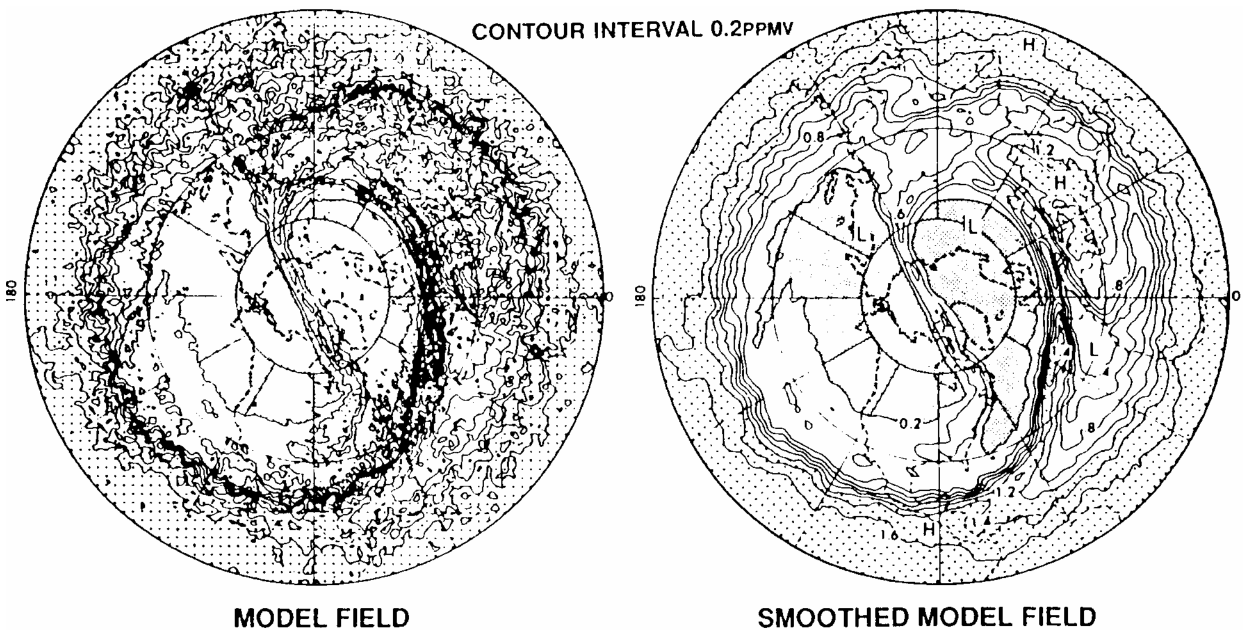

Figure 10.2—High resolution model simulation of a nitrous oxide field at 10 mbar (30 km) in the Northern Hemisphere on 25 January, produced by GFDL SKYHI GCM with 1° × 1° resolution and 40 levels (Mahlman and Umscheid 1987).

These figures show how current atmospheric sounders lag behind numerical models in their resolution, and hence in their ability to validate those models, especially the critical dissipative and mixing processes that take place within the models. The discrepancy will be even greater by the time of the first EOS launch. Given the increasing sophistication of numerical models, the lack of validating measurements will become the limiting factor in theoretical development.

The HIRDLS instrument will improve on the capabilities of previous limb scanners by incorporating cross-track scanning, to obtain a horizontal resolution of roughly 500 km (i.e., 5°). Furthermore, the vertical resolution will be increased to approximately 1 km, using an oversampling technique in which the radiances are measured at 0.2 km intervals. This method should allow 2 km vertical wavelengths to be resolved. The instrument will also be programmable, to provide higher horizontal resolution in swaths along the satellite track, for specific process studies, such as, detecting internal gravity waves.

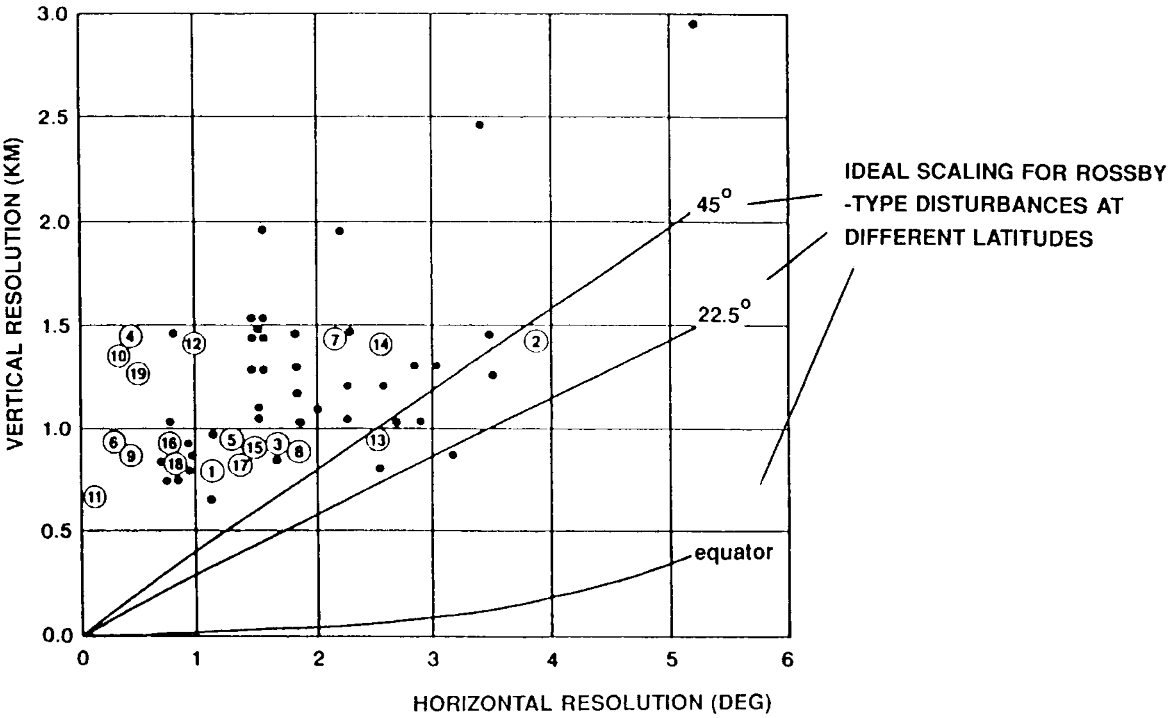

Figure 10.3—Vertical and horizontal resolutions that were used in post-FGGE general circulation and numerical models, denoted by both dots and circles (Lindzen and Fox-Rabinovitz 1989).

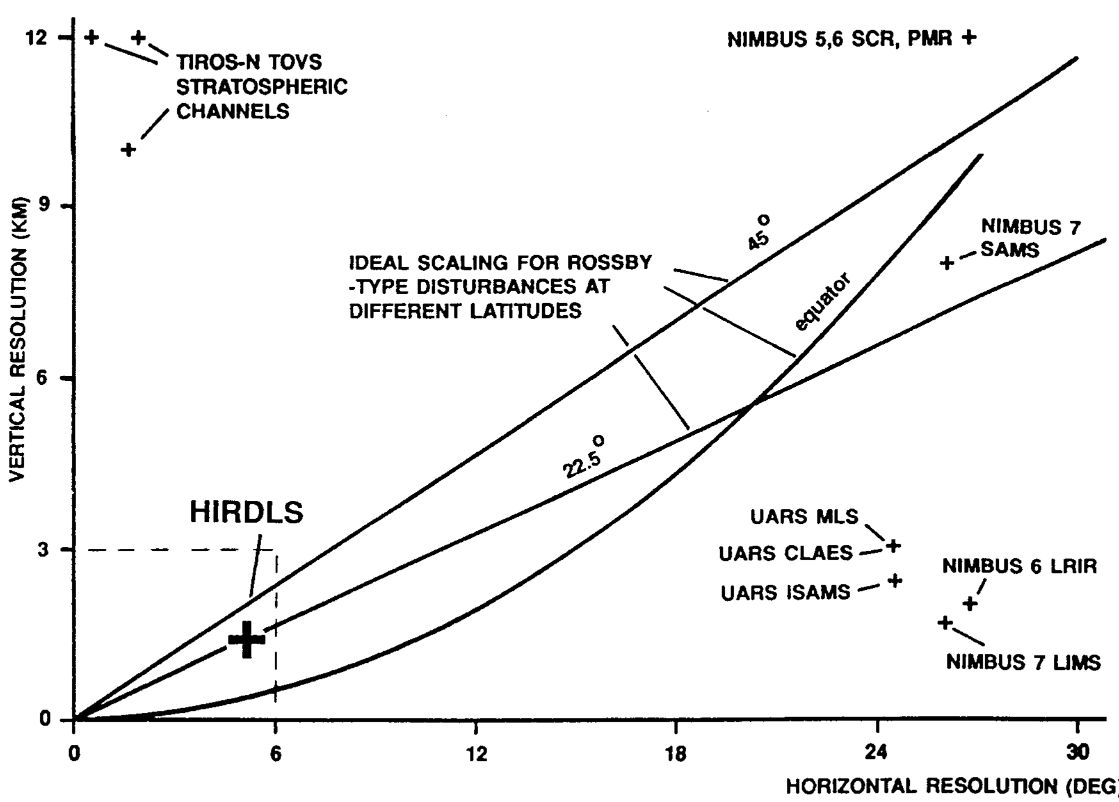

Figure 10.4—Resolution of the HIRDLS instrument compared to other sounders.

10.3 Long-Term Trends

Long-term changes are difficult to detect in a background of large natural variability, such as regular seasonal, annual, and eleven-year solar cycle changes. Interference from irregular interannual variability and the quasi-biennial oscillation are even more difficult to remove, and there are suggestions that some of these cycles are interlinked. Thus, in order to detect small trends that are caused by human activities and understand their causes, stable measurements of many key variables must be made over long periods of time.

A good knowledge of the trends of temperature and atmospheric constituent concentrations has proven to be extremely difficult to acquire. Changes in instrumental technique have masked these comparatively slow changes. In addition, only the most recent instruments were designed to make trend measurements. A data set that is based on five years of HIRDLS measurements will provide climatologies and delineate seasonal and interannual variability. The flight of three HIRDLS instruments at five-year intervals, as suggested in early EOS plans, would provide the potential for fifteen years of uninterrupted measurements with virtually identical characteristics, and with overlap between the operating periods. In addition, it should be possible to deduce trends by referring to measurements that were made by earlier instruments on the Nimbus satellites, UARS, and the NOAA operational series. It is important that the HIRDLS instrument be designed to take advantage of this opportunity. Which means it must be accurately self-calibrating in space, and it must undergo rigorous prelaunch characterization, with the specific intention of trend measurement.

10.4 Geopotential Height Gradients

Winds were derived from previous nadir and limb sounder measurements by integrating the vertical temperature profiles to obtain thicknesses. These thicknesses were added to the conventionally determined geopotential height of a low altitude pressure surface to determine the height of higher altitude surfaces. Then, these heights were used with geopotential or higher order approximations to derive the dominant nondivergent component of the wind. The conventional analytical methods may not be adequate at the horizontal resolution of the HIRDLS instrument, especially in data-sparse regions. The limb-sounding technique will be extended to directly measure the horizontal gradient of pressure surfaces. Wind fields will be derived from the temperature and geopotential fields, using either nonlinear balance approximations or assimilation techniques. Away from the equator, this is equivalent to measuring the dominant component of the wind at the base of the stratosphere. These data may also have a significant impact on tropospheric analyses.

11 Scientific Measurement Requirements

The scientific objectives that are outlined above translate into the overall measurement requirements that are given in Table 1. (The requirements for each specific scientific problem are listed in Table 2 at the end of this document.) The basic data products of the HIRDLS instrument will be the atmospheric temperature, the geopotential height gradient, and the mixing ratios of the constituents that are listed in Table 1 (viz., ten molecular gases, plus aerosol). These quantities will be gridded (i.e., mapped) horizontally, possibly by using assimilation techniques. Higher order derived quantities, such as potential vorticity, will be calculated from the basic data products (for use in some of the studies that are discussed above), and they will be made available as operational data products.

Table 1—HIRDLS Measurement Requirements

Temperature:			
	< 50 km	0.4 K precision	1 K absolute
	> 50 km	1 K precision	2 K absolute
Constituents:			
	O_3, H_2O, CH_4, N_2O, NO_2, HNO_3, N_2O_5, $ClONO_2$, CFC 11, CFC 12	(1 to 5) % precision	(5 to 10) % absolute
	aerosol, spectral channel extinctions	(1 to 5) % precision	25 % absolute
Horizontal geopotential height gradient		20 m / 500 km	(vertical / horizontal)
	(equivalent 60°N geostrophic wind)	(3 $m \cdot s^{-1}$)	
Coverage:			
	horizontal	global, 90°S to 90°N	(must include polar night)
	vertical	upper troposphere to mesopause	(8 km to 80 km)
	temporal	long-term, continuous	(five years unbroken)
Resolution:			
	horizontal	profile spacing of ≤ 5° latitude and longitude	
	vertical	(1 to 1.25) km	
	temporal	complete field in 12 h	

12 Basic Data Products

The basic data products of the HIRDLS instrument, as listed in Table 1, will be: atmospheric temperature, geopotential height gradient, mixing ratios of atmospheric constituents, and spectral extinction coefficients. The temperature, mixing ratios, and a measure of the aerosol amount will be gridded horizontally. The direct geopotential measurement by the HIRDLS instrument will give an accurate representation of the variation of geopotential heights between soundings, but it will require periodic recalibration from ground-based data or tropospheric analyses, in order to produce consistent global geopotential fields. Aerosol characteristics will be derived from the spectral variation of the extinction. Wind fields will be computed from the temperature and geopotential fields by using either nonlinear balance approximations or assimilation techniques. Higher order derived quantities, such as potential vorticity, will be calculated from the basic data products. All of the above fields will be made available to other EOS investigators.

13 Summary

The stability of the ultraviolet radiation shield of stratospheric ozone is one of the critical issues of global change. Over the next few decades, in response to the Montreal Protocol, we expect stratospheric concentrations of CFCs to level out and then decrease, perhaps resulting in a turnaround in the decline of ozone. Such a turnaround has yet to be documented, in either ozone or UVB trends. On the other hand, if present trends continue, increased quantities of other gases, such as CO_2, CH_4, N_2O, and possibly H_2O, will affect the concentration of ozone through a variety of chemical and thermodynamic interactions. The roles of CFC replacement compounds in the chemical depletion of stratospheric ozone are still unexplored. The discovery of the antarctic ozone hole, the identification of the key roles that are played by polar stratospheric clouds, heterogeneous chemistry, and large-scale dynamics during the formation of the hole, and the discovery of similar processes during the formation of the winter polar vortex in the Arctic underscore the need to fully observe the interactions between chemistry, fluid dynamics, and radiation, in order to understand the behavior of stratospheric ozone.

To observe this complex system and monitor its behavior as it is perturbed by human activity, volcanic activity, and solar variability, global measurements must satisfy several criteria. The vertical and horizontal scales at which dynamical and chemical processes are producing significant variability must be well observed. There must be coincident measurements of ozone concentration, dynamical parameters, and concentrations of other key species in the photochemical families with which ozone interacts. High vertical and horizontal resolution measurements must cover the lower stratosphere (below about 25 km), where most of the ozone is stored. The measurements should extend upward through the region where rapid chemical processing takes place, namely, the upper stratosphere and mesosphere, and they should extend downward at least to the tropopause, where stratosphere-troposphere exchange occurs. These observations must extend over several years to measure interannual variability, and over many years to determine trends. In addition, the extension of some measurements into the upper troposphere would help to unravel the complex upper tropospheric interactions between ozone and other downward-mixing stratospheric species, or upward-mixing species, such as CO.

The HIRDLS experiment will build on the UARS measurements, by extending the observations downward to the tropopause region and below. The lower stratosphere and the tropopause region have been notoriously difficult to observe adequately. For the first time, the HIRDLS instrument will obtain precise relative measurements of the geopotential height of constant pressure surfaces in the lower stratosphere. This will make it possible to deduce the pressure field over the entire globe, from the tropopause to the upper mesosphere, on the same grid as the temperature and constituent measurements. Also for the first time, the HIRDLS instrument will obtain global measurements at the small horizontal scales that are important for the mixing of mass, momentum, potential vorticity, and constituents by breaking waves. The resolution will be superior to that of any other instrument that has been proposed for any EOS or NOAA satellite. On EOS, these observations will extend over a long enough period of time to study problems of interannual variability and trends. One particularly important contribution from the HIRDLS observations will be the determination of the global climatology of the internal gravity waves that have horizontal wavelengths which exceed a few hundred kilometres over the entire observed altitude range. The HIRDLS instrument will routinely measure Kelvin, Rossby-gravity, and Rossby waves, including their interactions with the zonal mean flow and the upper troposphere. These measurements will provide significantly better information with which to determine the mechanisms of interannual variability.

Progress on any scientific problem ultimately depends upon adequate measurements. The problem of understanding climate change requires simultaneous measurements of dynamical, thermodynamical, and chemical properties at high resolution in the middle atmosphere, as well as in the troposphere. HIRDLS measurements, used in conjunction with current theoretical understanding and suitable numerical modeling, will greatly increase our understanding of climatic mechanisms, from the upper troposphere to the upper mesosphere.

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Mahlman, J. D., and Umscheid, L. J. 1987, in *Transport Processes in the Middle Atmosphere*, ed. G. Visconti and R. Garcia (Dordrecht: D. Reidel), p. 251.

Table 2—HIRDLS Science Requirements

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[1]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
mass budget for dry air	wind field[2] ⇓ divergence of the Eliassen-Palm flux ⇓ transformed Eulerian mean residual vertical velocity ⇓	$T(p)$	1 km	stratopause (≈ 1 mbar) to 300 mbar	5° × 5° (550 km × 550 km, at the equator)	global	$T < 0.5$ K	$T < 2.0$ K

[1]The sampling and precision needed to resolve 2 km vertical wavelengths.

[2]Wind and potential vorticity fields are first level derived quantities and are used in many subsequent problems.

	temporal and zonal mean air mass exchange across an isobaric surface							

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[3]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
budget of chemical constituents	vertical transport of trace species	constituent fields with tropospheric origin (H_2O, CH_4, N_2O, CFC 11, and CFC 12) and stratospheric origin (O_3, NO_2, HNO_3, and $ClONO_2$)	1 km	stratopause (≈ 1 mbar) to 300 mbar	5° × 5° (550 km × 550 km, at the equator)	global	VMR < 10 %	VMR < 20 %

[3]The sampling and precision needed to resolve 2 km vertical wavelengths.

exchange rates across subtropical jets	correlation of tracer concentration with mass flow	$T(p)$ and tracer VMR	1 km	70 mbar to 150 mbar	5° × 5°	global	minimum of 0.5 ppmv for O_3 and H_2O	VMR < 20 %

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[4]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
quasi-horizontal mixing in regions of large PV gradients	correlation of eddy mixing with tracer concentration	$T(p)$ and tracer VMR	1 km	20 mbar to 300 mbar	smallest scale possible, maximum spacing of 200 km × 200 km	global	TBD	T < 2.0 K and VMR < 20 %
polar vortex boundaries								
tropopause breaks								
wave breaking				0.1 mbar to 100 mbar	5° × 5° and 2° × 2° (as a special case)			

[4]The sampling and precision needed to resolve 2 km vertical wavelengths.

explosive cyclogenesis over oceans	mass flow and tracer concentration	$T(p)$ and tracer VMR	1 km	10 mbar to 300 mbar	5° × 5°	global	T < 0.5 K and VMR < 10 %	VMR < 20 %

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[5]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
planetary waves[6]	correlation of planetary waves with EP flux divergence, temperature, and wind distributions	$T(p)$	1 km	1 mbar to 300 mbar	5° × 5°	global	TBD	T < 2.0 K and VMR < 20 %
gravity waves	correlation of gravity waves with orographic forcing and forcing by convection	$T(p)$	1 km	above 300 mbar	200 km × 200 km	global	0.2 K	

[5]The sampling and precision needed to resolve 2 km vertical wavelengths.

[6]Long life will increase the probability of observing formation and evolution of blocking patterns.

gravity waves	wave drag residual in the momentum budget	$T(p)$	1 km	0.01 mbar to 100 mbar	5° × 5°	global	0.2 K	

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[7]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
equatorial semiannual oscillations	wave drag residual in the momentum budget	$T(p)$	1 km	0.05 mbar to 100 mbar	5° × 5°	global	0.5 K	
equatorial quasibiennial oscillations	wave drag residual in the momentum budget	$T(p)$	1 km	10 mbar to 100 mbar	5° × 5°	global	0.5 K	
inertially unstable waves			6 km					
unstable Rossby waves								

[7]The sampling and precision needed to resolve 2 km vertical wavelengths.

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[8]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
polar chemistry[9]								
polar stratospheric cloud distribution	correlation of PSC locations with temperature	$T(p)$ and aerosol	1 km	10 mbar to 300 mbar	200 km × 200 km	polar regions	$T < 0.5$ K	
PSC-influenced chemistry	correlation of PSC locations with disturbed chemistry	$T(p)$, O_3, H_2O, NO_2, HNO_3, $ClONO_2$, and aerosol	1 km	10 mbar to 300 mbar	200 km × 200 km	polar regions	$O_3 < 2$ % and $HNO_3 < 5$ %	
vortex downward transport	vertical mass motions and passive tracer concentration	$T(p)$, CH_4, N_2O, CFC 11, and CFC 12	1 km	10 mbar to 300 mbar	200 km × 200 km	polar regions		

[8]The sampling and precision needed to resolve 2 km vertical wavelengths.

[9]Interannual variations require several years of observation.

vortex evolution and processing	long-term interior and exterior vortex chemical composition	$T(p)$, O_3, H_2O, N_2O, NO_2, HNO_3, N_2O_5, and $ClONO_2$	1 km	10 mbar to 300 mbar	5° × 5°	polar regions		

Table 2—Continued

Scientific Problem	Derived Quantity	Geophysical Parameter	Vertical Resolution[10]	Vertical Coverage	Horizontal Resolution	Horizontal Coverage	Precision	Accuracy
ozone and temperature relationships		$T(p)$ and O_3	1 km	10 mbar to 300 mbar	200 km × 200 km			
odd nitrogen and odd hydrogen budgets		H_2O, CH_4, N_2O, NO_2, HNO_3, N_2O_5, and $ClONO_2$	1 km	10 mbar to 300 mbar	200 km × 200 km			
chemical processes			1 km	10 mbar to 300 mbar	200 km × 200 km			
long-term trends[11]	long-term chemical composition	$T(p)$, O_3, H_2O, CH_4, N_2O, NO_2, HNO_3, $ClONO_2$, CFC 11, and CFC 12	1 km	1 mbar to 300 mbar	5° × 5°	global		$T < 0.5$ K, $O_3 < 2$ %, and tracers < 10 %

[10]The sampling and precision needed to resolve 2 km vertical wavelengths.

[11]A minimum of five years of observation is required.