Global Constellation of Stratospheric Scientific Platforms

Earth Science Rationale and Mission Scenarios

Global Aerospace Corporation

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Preface

The purpose of this report is to illustrate how balloon-born in situ instrumentation on advanced global stratospheric balloon constellations can be used help answer some of the key questions we face regarding global change. We show that developing both the technologies for implementation of this approach as well as utilizing *in situ* balloon-borne instrumentation is consistent with the recent recommendations of a large body of atmospheric scientists.

We present selected mission scenarios that have objectives of answering scientific questions that are part of NASA's mission. These mission concepts describe measurements from regional and global constellations of ultra long duration balloon-borne scientific stratospheric platforms. These example concepts have been developed based on our current understanding of science priorities and the extrapolations of technological developments in measurement capabilities. We hope and anticipate that this report will be a living document, providing impetus and focus for input and development from the broader scientific community.

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1 Introduction

Global constellations of stratospheric scientific platforms are described, and a perspective on future directions in earth science is given, which help to place this new concept in the context of NASA's Earth Science Mission.

1.1 Global Constellations of Stratospheric Scientific Platforms

Global Aerospace Corporation is developing, under NASA Institute of Advanced Concepts funding, a revolutionary concept for a global constellation and network of perhaps tens to hundreds of stratospheric superpressure balloons. A network of balloons can address major scientific questions relating to NASA's *Earth Science Mission*, by globally measuring stratospheric gases, collecting data on atmospheric circulation, observing the Earth's surface, and detecting and monitoring environmental hazards.

Each balloon will be designed to operate at an altitude of 35 km for up to 5 years in duration. The key stratospheric platform technologies required for an affordable, very long-duration, global balloon constellation are innovative balloon designs, advanced balloon envelope materials and fabrication, lightweight and efficient power generation and energy storage, and balloon trajectory control. Developing technology for very long-duration and guided stratospheric balloons will enable an affordable global constellation of formation-flying, stratospheric platforms. The structure of the global constellation of balloons will be maintained by sophisticated trajectory control algorithms with inter-platform communication facilitated by the emerging global communications infrastructure. The technology for such very long duration balloon systems is critically dependant on the current development of NASA's ultra Long Duration Balloon (ULDB) Project which is expected to demonstrate 100-day flight missions by the end of 2000. Figure 1 illustrates the constellation concept.

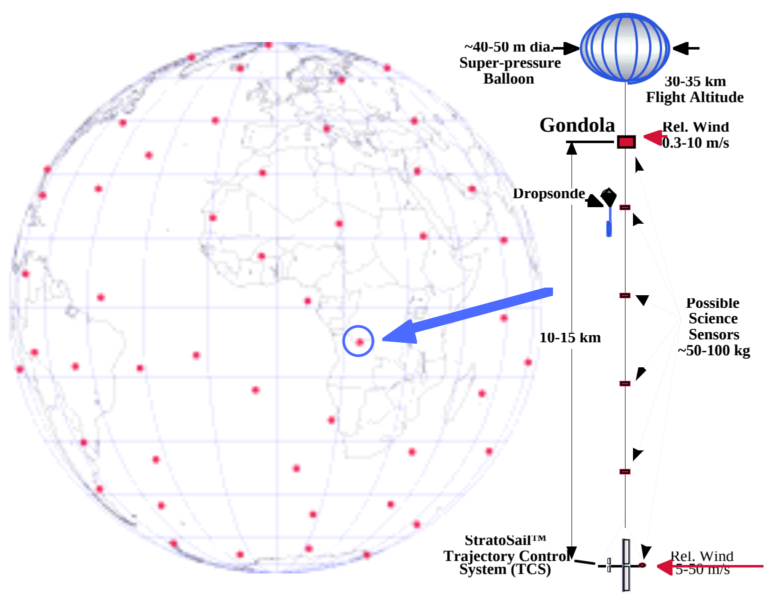

Figure 1. Global Constellation of Stratospheric Scientific Platforms

1.2 Earth Science Perspective

Whether mankind’s role on planet Earth is viewed from a religious or secular vantage point, it is clear that we are entrusted with it’s guardianship. Whether it is maintaining an international framework providing for peaceful coexistence between nations trying to avoid rapid destruction and global devastation through a nuclear holocaust, or a similar framework to prevent harmful and potentially irreversible damage to our planet through our own neglectful or irresponsible behavior, it is incumbent on government leaders to provide the ways and means to do this. Within the past 50 years, we have become aware of many and diverse examples of human induced global change. With the continued rapid growth in the world’s population, this trend can only be reversed through worldwide cooperative vigilance and action. To quote Dan Albritton, a Director of the NOAA Aeronomy Laboratory: “Understanding our global environment and our role in it is the first step towards living in harmony with it.” While following this advice may seem straightforward, developing and carrying out an efficient cost-effective plan with the proper priorities and vision require significant, flexible, and continuous stewardship.

In the United States, this job has been entrusted to the U. S. Global Change Research Program (USGCRP) which coordinates the efforts of many Federal agencies. According to Ghassem R. Asrar, Associate Administrator for Earth Science, “NASA’s Earth Science Enterprise turns its space-based observing technology and scientific expertise to the study of our home planet. This Earth Science Strategic Enterprise Plan maps out NASA's strategy for observation and research on our home planet for the next 5 years (1998–2002), or through the deployment of the first series of Earth Observing System missions. This 5-year strategy is set in the context of a 25-year roadmap for the future. Concurrently, we have initiated a process to define science questions and mission strategies for the 5 or more years beyond this time horizon. This effort will incorporate the results of the National Academy of Sciences' report on pathways for global change research for the next decade.”

The NASA Earth Science Enterprise (ESE) has identified five research questions as the focus of effort for the next several years.

- What are the nature and extent of land-cover and land-use change and the consequences for sustained productivity?
- How can we enable regionally useful forecasts of precipitation and temperature on seasonal to interannual time frames?
- Can we learn to predict and mitigate natural disasters?
- What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?
- How and why are concentrations and distributions of ozone changing?

Based on the global nature of these questions, it is correctly argued that to study these issues, requires understanding how the earth works as a system. It is further argued that “the spatial, temporal, and spectral coverage offered by modern space-based instrumentation best addresses the requirements of researches for long time series of data”[Asrar and Dozier, 1994]. These authors develop the premise that the focus of research for understanding our changing planet should be space-based. They further argue that only satellites can provide systematic and continuous monitoring of the earth’s atmosphere for a minimum for 15 years to be able to distinguish between anthropogenic and natural changes. However, alternate points of view on this matter can be presented. For example, there is a significant difference between detecting a change which can be identified as anthropogenic, and making progress in determining the cause for that change. While it is certainly helpful to make the appropriate measurements to for example observe a decrease in air quality in urban regions, without understanding the mechanistic cause of the pollution, any regulations put in place to improve air quality might impose economic hardship on the local community without any noticeable benefit. The question has to be raised as the long term strategy needed to strike a proper balance between space-based monitoring and approaches which in the context of the global perspective provided by satellite data can address key mechanistic questions regarding anthropogenic global change. According to a description of the program,

"ESE seeks to maintain a balanced program across the earth science disciplines and among the various ESE program elements. In most cases this does not imply equivalent resource allocation. We strive to achieve balance in the following key areas:

- *In situ observations and space-based observations needed for more complete information for calibration/validation purposes.*
- *A broad spectrum of Earth System Science research with a contemporary focus on climate change."*

However, it is not clear how the proper balance is determined. For example, satellites monitoring global, ozone mixing ratios, both total column and as a function of altitude, were not the first instruments to identify the existence of an Antarctic ozone hole. The hole was first identified using in situ ozone sonde data [Farman and Gardiner, 1987]. After two years of scientific postulating as to the many possible causes of the ozone hole, simultaneous in situ ozone and chlorine monoxide measurements on an ER-2 NASA research aircraft, which flew into the hole, provided unambiguous evidence that chlorine, with an increasing anthropogenic source, was catalytically destroying ozone [Anderson *et al*., 1989]. It is only with this level of scientific analysis that governments can effect policy on a national and worldwide basis to reverse deleterious environmental trends.

These measurements were carried out as part of the Antarctic Ozone Expedition (AAOE). Key questions have similarly been addressed by missions on aircraft or aircraft and balloons. NASA sponsored campaigns such as the Airborne Arctic Stratospheric Expedition (AASE), the Stratospheric Tracers of Atmospheric Transport (STRAT), the Photochemistry of Ozone Loss in the Arctic Region In Summer (POLARIS), have provided advances in our understanding of ozone depletion processes and stratospheric circulation. Additionally, National Science Foundation (NSF) sponsored campaigns in the tropics have similarly investigated problems relating to climate.

These missions have provided extremely useful data, representing a unique way to make simultaneous measurements of a number of key atmospheric species. However, such missions are both difficult to organize and extremely expensive to fund. Accordingly they occur only at intervals in time such that they often miss the events they have been organized to study. For example, SAGE (Stratospheric Ozone and Aerosol Experiment) Ozone Loss and Validation Experiment (SOLVE) a planned mission to Sweden to study the polar ozone hole and provide *in situ* validation and calibration data has taken about 18 months to organize. It will take place even though delays in launching the satellite will prevent the satellite validation from occurring. It will take place whether or not local meteorology is suitable for significant ozone depletion.

Additionally, current aircraft capabilities limit measurements to 20 km. Most of the ozone depletion occurs above this altitude range. While satellite-borne instruments can observe this region, they can not provide the resolution necessary for doing mechanistic studies. The vast part of the stratosphere has only sporadic in situ measurements on balloons. The importance of these measurements can be seen by the role they are taking in the SOLVE mission and in tropical missions.

A critical question facing the USGCRP is what is the proper balance between space-based, surface-based, and *in situ* measurements to most efficiently address the key questions facing our changing environment, and in the face of diminishing resources, what is the proper balance of funding to achieve our goals.

The purpose of this report is to illustrate how balloon-born in situ instrumentation on advanced very long duration balloons in small networks and as part of a global stratospheric constellation of 100 or more balloons or *StratoSats*, can and should be used help answer some of the key questions we face regarding global change. We plan to document how or show that developing both the technology for implementation of this approach as well as utilizing *in situ* balloon-borne instrumentation is consistent with the recommendations of a large body of atmospheric scientists who have within the last 5 years participated in workshops or in writing monographs specifically organized to address issues as this. We will reference two such reports to provide strong evidence of the role StratoSats can play in the future study of global change.

2 Global Change Research - Future Plans and Prospects

A committee on global change research was charged by the National Academy of Sciences and the National Oceanic and Atmospheric Administration with “reviewing the current status of the USGCRP with a view toward defining the critical scientific questions in the Program’s four areas of concentration.” As a result 1998 they published a report called *Global Environmental Change: Research Pathways for the Next Decade.*

2.1 Report Goals

The USGCR Program’s four areas of concentration include seasonal to interannual climate prediction, decadal to centennial climate change, atmospheric chemistry, and terrestrial and marine ecosystems. The committee on global change research was charged with preparing a report that would (1) articulate the central scientific issues posed by global change; (2) state the key scientific questions that must be addressed by the USGCRP; and (3) identify the scientific programs, observational efforts, modeling strategies, and synthesis activities needed to attack these scientific questions.” [Global Environmental Change: Research Pathways for the Next Decade, 1998]. The results of this report are to be incorporated into the ESE effort. We therefore enumerate some of the recommendations of that report.

2.2 Recommendations

2.2.1 Recommendation Two

An outcome of the Pathways Report is a series of recommendations regarding research in global change. We list here those recommendation which are of relevance to this proposal. <u>*Recommendation Two*</u> states that the strategy for earth observations be restructured and must be driven by key unanswered scientific questions. These questions are listed and elaborated below. It is vital that the observational capability be developed to support the research addressing critical common themes:

- Understanding the earth’s carbon and water cycles
- Characterizing climate change
- Elucidating the links among radiation, dynamics, chemistry, and climate.

2.2.2 Recommendation Three

<u>*Recommendation Three*</u> states that the strategy must be reassessed for obtaining long term observations designed to define the magnitude and character of Earth system change. The strategy must take into account the overall balance between space-based and *in situ* observations. Additionally, the fact that long term observing systems have been designed for purposes other than long term accuracy [what other purposes] and that this has undercut the long term calibration needed for scientific understanding of global change.

2.2.3 Recommendation Four

Recommendation Four states that the restructured national strategy for Earth observations must more aggressively employ technical innovation. Resources should be reallocated to a more agile, responsive ensemble of observations.

3 The Atmospheric Sciences: entering the 21st century

Atmospheric Sciences entering the 21st century, published in 1998 as a report of the National Academy of Sciences, was written as the results of a workshop by an international group of distinguished scientists, and represents the a consensus of the atmospheric science community.

3.1 Report Organization

The report is divided into two main sections. The first focuses on scientific imperatives and recommendations for the decades ahead. The second part discusses in detail recommended scientific goals within 5 disciplines: Atmospheric Physics research; Atmospheric Chemistry research; Atmospheric Dynamics and Weather Forecasting research; Upper-Atmosphere and Near-Earth Space Research.; and Climate and Climate Change Research.

3.2 Report Imperatives

The Board's two highest priority recommendations are designated as imperatives and are quoted here:

Imperative 1. Optimize and integrate atmospheric and other Earth observation, analysis, and modeling systems.

Imperative 2. Develop new observation capabilities for resolving critical variables on time and space scales relevant to forecasts of significant atmospheric phenomena.

These imperatives which are broad and comprehensive, and recommend **optimizing global observations of the atmosphere** and **the development of new capabilities for observing critical variables** in the atmosphere. "The plan should take into account requirements for monitoring weather, climate, and air quality and for providing the information needed to improve predictive numerical models used for weather, climate, atmospheric chemistry, air quality, and near-Earth based physics activities." The nature of new and recently developed methods of acquiring atmospheric observations, such as commercial aircraft observations [Cho *et al*., 1999]) and Global Positioning Satellites [Kursinski et al., 1996]) suggest that the "observing system of the future may be dramatically different from that of today. Also, "high resolution measurements in specific locations may enhance prediction of specific phenomena".

These imperatives provide a strong argument in support of in situ balloon instrumentation.

3.3 Recommendations

The second section of this book recommends specific areas of research and enumerates key questions that need to be addressed, in each of the five broad areas of research outlined. We list these below to illustrate areas of research in which scientific payloads as part of global and regional constellations of advanced technology balloons can play a critical role in global change research.

3.3.1 Atmospheric Physics Research

- Develop observational studies and analyses to (1) better utilize satellite and remote sensor data; (2) represent the four-dimensional distribution of water vapor, and (3) quantify the direct radiative forcing of climate by trace gases and aerosols.
- Develop and/or test radiative transfer in cloudy atmospheres. A significant challenge exists in obtaining simultaneous combined data sets characterizing the microphysical and radiative properties of clouds, and the distribution of temperature and water vapor.
- Develop the ability to predict the extent, lifetimes, and microphysical and radiative properties of stratocumulus and cirrus clouds. Both model simulations and observations have revealed that cloud-radiative interactions play a significant role in climate and climate change. We need to know the sensitivity of cloud condensation nuclei (CCN) and ice nucleus populations to global temperature, solar radiation, surface humidity, and soil characteristics.
- Investigate the interactions among aerosols, trace chemical species, and clouds and improve the characterization of aerosols.
- The effects of species having short lifetimes and pronounced spatial and temporal variability, e. g. tropospheric and stratospheric aerosols and ozone (O_3), should be evaluated accurately in order to understand their effects on climate.

3.3.2 Atmospheric Chemistry Research

- Stratospheric ozone challenges: Document the distributions, variability, and trends of stratospheric ozone and there key species that control its catalytic destruction.
- Elucidate the processes that control the abundance and variability and trends of atmospheric carbon dioxide CO_2), methane (CH_4), nitrous oxide (N_2O), ozone and water vapor (H_2O), and expand global monitoring of upper tropospheric and lower stratospheric H_2O and O_3.
- Document the chemical, physical, and radiative properties of atmospheric aerosols their spatial extent, and log term trends.
- Document the chemical physical and radiative properties of aerosols, their spatial extent and their long-term variability.

4 Scientific Ballooning

Scientific ballooning has played, and will continue to be a part of atmospheric science research. We will not discuss in this context the role of sondes, small balloons carrying operational instruments which take data on ascent until the balloons burst, but rather balloons carrying research instruments that take data on ascent, float and descent and weigh up to hundreds of kilograms. These instruments provided most of the stratospheric data until the advent of space-based instrumentation. They continue to provide calibration and validation data for satellite data sets, as well as high resolution measurements not achievable by satellite measurements. At a Workshop for Integrated Satellite Calibration/Validation and Research-Oriented Field Missions in the Next Decade (fall 1999 Snowmass, CO) Professor William Brune of Pennsylvania State University presented a talk concerning the role of conventional balloon borne atmospheric science payloads. He stated that balloon -borne measurements have unique validation and science capabilities and summarized their strengths as weaknesses as follows:

"Strengths:

- Cover stratosphere and troposphere from 40 to 10 km, [much of this] above aircraft [altitudes].
- Provide simultaneous measurement of multiple species.
- Provide high-resolution vertical profiling across large pressure range.
- Simulate remote sensing footprint of limb sounding satellites.

Weaknesses:

- Provide infrequent measurements, except for small balloons or in intensive mode.
- Give only vertical profiles – no probing of horizontal gradients.
- Are sometimes questionably cost effective for science and validation gained[due to limited mission duration]".

We note briefly here that while all the strengths listed above are valid for the new class of very long duration stratospheric platforms, all the weaknesses tabulated above are made moot by this new technology. Furthermore, typical scientific ballooning experience has involved spending a year or more preparing a payload, and 3 weeks at a launch site becoming flight ready and waiting for calm weather enabling a launch opportunity and perhaps a 1-15 day flight. Also, landing often results in damage to the payload. All these together can make conventional scientific ballooning a frustrating operation. Again the this new class of stratospheric platforms provides a major leap forward in return on investment of time and money.

5 Example Constellation Science Mission Scenarios

Within the context of the areas of global change that are being addressed by the Earth Science Enterprise (ESE), the recommendation of the Pathways report and the monograph, *Atmospheric Sciences entering the 21st century*, and the specific areas of research/ scientific questions to be answered within the context of environmental global change, we enumerate here a set of scientific observations from a network of tethered balloon platforms. This can in no means be thought of as a comprehensive set, but rather as one representative of the types of observations that can be made, the flexibility of this approach in terms of the ability to reposition platforms to observe specific seasonal or geographical environmental issues. Because, as evidenced by our experience with ozone depletion, the planned network would be in position to observe the unpredicted events as they happen.

It is also important to understand that because of the nature of the instrumentation proposed on the balloon platforms, that calibration and long term accuracy are a critical part of this plan, and the nature of the platform is amenable to this. We will emphasize this in each of the areas of research that we discuss. We will also choose sample payloads for which we project detailed information on the scientific instrument package.

5.1 Summary of Earth Science Mission Scenarios

The following is an example list of Earth science missions for global and regional constellations of stratospheric platforms that address major Earth science issues. Each of these example are discussed in more detail below.

A. Global Change Studies
  1. Water Vapor and Global Circulation in the Tropics
  2. Radiative Studies in the Tropics
  3. Global Radiation Balance
B. Ozone Studies
  1. Mid-latitude Ozone Loss
  2. Polar Ozone Loss
  3. Global Distribution of Ozone
C. Hurricane Forecasting and Tracking
D. Global Circulation and the Age of Air
E. Global Ocean Productivity

5.2 Climate Change Studies

The following concepts focus on climate change research.

5.2.1 Water Vapor and Global Circulation in the Tropics

It is currently understood that air enters the stratosphere in the tropics from where it slowly rises and heads poleward. Key issues regarding global change involve the water vapor mixing ratio in the upper troposphere, the mechanism that controls the water vapor mixing ratio entering the stratosphere, and the rate in which the air and that water vapor mixing ratio is transported poleward. Questions of ascent velocities in the tropical stratosphere are critical in understanding the general circulation. Stratospheric models need data on these velocities on an ongoing basis. Current approaches rely on aircraft borne, a few balloon-borne CO_2 profiles and some radiative transfer calculations to determine ascent velocities. Both carbon dioxide and water vapor exhibit seasonal cycles with water vapor ranging from a 3 ppmv minimum Northern Hemisphere (NH) winter to 6 ppmv in the summer. CO_2 exhibits varies by about 3 ppmv with its maximum in NH fall and minimum in spring. Measurements of carbon dioxide at the surface and at the tropical tropopause have served to characterize its variability very well. The phasing of the water vapor signal is well understood from satellite measurements and in situ measurements have started to provide accurate quantitative information on its seasonal cycle. Measurements of CO_2 and water vapor have already been used to give ascent velocity information but the data is sparse. The availability of continuously measured water vapor and CO_2 profiles from the tropopause up into the middle stratosphere would provide invaluable information for stratospheric circulation and would help provide better understanding of the overall lifetime of atmospheic species. . These data would also provide the first picture of the interannual variability of atmospheric circulation. It would address issues involving our understanding of how much water enters the stratosphere on an annual basis and provide a basis for our understanding trends or variability in stratospheric water which have been observed by satellites and sonde data.

Accurate high-resolution measurements of upper tropospheric water are critical for our understanding of global warming. Water vapor is the principle greenhouse gas and measurement of its concentration in the upper tropical troposphere, along with concurrent ozone and temperature measurements from about 12 to 18 kilometers is critical. Satellite-based measurements can provide neither the resolution nor the accuracy needed in the tropopause region where ozone and water vapor mixing ratios vary significantly with altitude.

Because this payload provides a direct measurement of global circulation, it has direct impact on two of the identified ESE research questions:

- What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?
- How and why are concentrations and distributions of ozone changing?

It also provides information potentially useful for the following two ESE research questions because of the critical role atmospheric circulation has in weather related issues on a global scale:

- How can we enable regionally useful forecasts of precipitation and temperature on seasonal to interannual time frames?
- Can we learn to predict and mitigate natural disasters?

This payload also would satisfy the goal expressed in imperative 2 in the monograph, *Atmospheric Sciences entering the 21st century*, as well as recommendations 2,3, and 4 of the pathways report. For example, this experiment addresses the following points in the Pathways report:

- Understanding the earth's carbon and water cycles
- Characterizing climate change
- Elucidating the links among radiation, dynamics, chemistry, and climate.

These experimental techniques address Recommendation Three of the Pathways report that states that *the strategy for obtaining long term observations designed to define the* *magnitude and character of Earth system change must be reassessed. The strategy must take into account the overall balance between space-based and in situ observations. Additionally, the fact that long term observing systems have been designed for purposes other than long term accuracy and that this has undercut the long term calibration needed for scientific understanding of global change*. They also address Recommendation Four that states that *the restructured national strategy for Earth observations must more aggressively employ technical innovation. Resources should be reallocated to a more agile, responsive ensemble of observations*.

We would envision 35-50 of these payloads from 15 S to 15 N latitude. This coverage will map out the seasonal, latitudinal and longitudinal dependence of the flux into the lower tropical stratosphere. The payload configuration is schematically represented in Figure 2. The payload consists of a microwave temperature profiler at the Trajectory Control System (TCS), water vapor and LIDAR instruments at the gondola, and *in situ* water vapor ozone, instruments on the tether and CO_2 on the sail. A new *in situ* absorption technique called cavity ringdown laser absorption spectroscopy using a multipass cell will provide high accuracy. For CO_2, where 0.1 ppmv accuracy is the goal, a small gas addition system will be used to periodically calibrate the instrument.

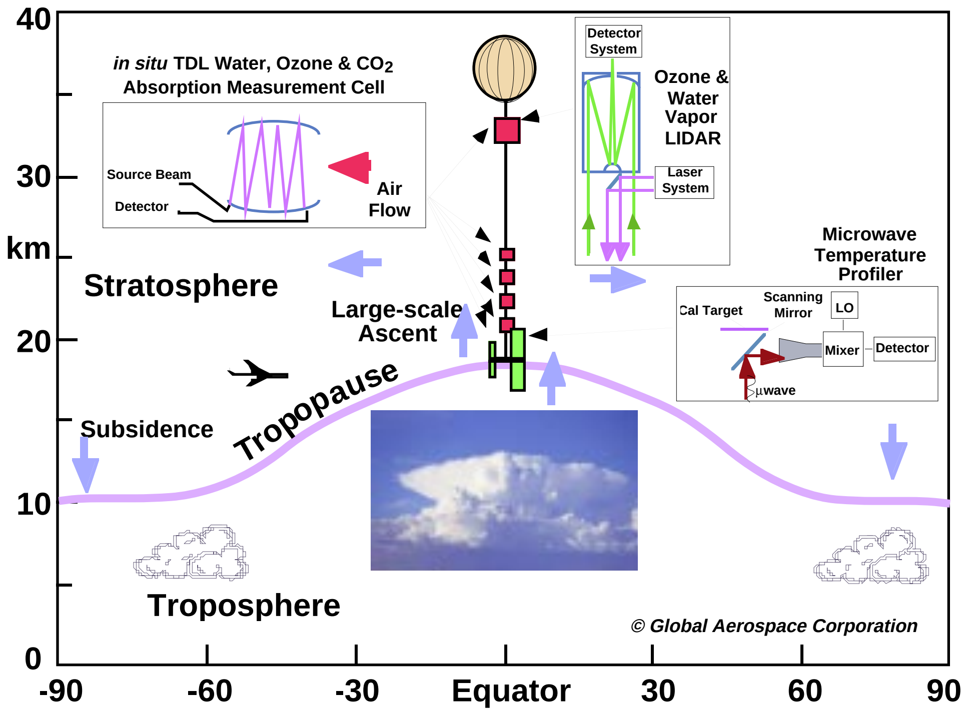

Figure 2. Climate Change: Dynamical Processes in the Tropics

5.2.2 Radiative Studies in the Tropics:

The payload described below addresses two of the specific categories of research listed in Recommendation Two of the Pathways report, *characterizing climate change*, and *elucidating the links among radiation, dynamics, chemistry, and climate*. It will also provide information to four of the bullets in the atmospheric physics category taken from *The Atmospheric Sciences: entering the 21st century* and listed above. Issues of global warming and how to determine whether we are experience it or not has been a focus of serious debate within both the scientific and political communities. It is well understood that much of the infrared radiation that escapes the earth does so in the dry or downwelling regions of the tropics, where the relative humidity is low enough. Monitoring the emitted radiation of the atmosphere from the near to far infrared in this region with an accurately calibrated Fourier Transform Infrared Radiometer will provide invaluable information on climate change. While projected satellite based instrumentation will provide a global picture, resolution from a satellite often is insufficient to clearly isolate homogeneous regions. However, balloon-borne instruments have a small enough “footprint” to do just that. Additionally, by providing a cloud LIDAR instrument with the same footprint, both through verification of clear sky as well as through the measurement of change in emission in the presence of clouds at specific altitudes, these measurements will provide a thorough determination of the radiative feedback properties of optically thick and thin cirrus clouds.

Scientifically, simultaneous measurements on the particle size distribution in clouds would allow a relationship between the particle size and its infrared properties to compare with models. Additionally, information will be provided on the radiative properties of aerosols. Aerosols have been found to play both a direct and indirect role in climate change. Calculations show that the direct contribution of aerosols is a cooling effect of on average about -2.5 W/m^2 which is significant relative to greenhouse gases. Unfortunately, understanding the details of aerosols and their radiative properties requires simultaneous measurements of their size distribution and particle density as well as their radiative effects. The study of the radiative properties of aerosols has been severely limited because or the difficulty of doing such an experiment. While there are in situ measurements from aircraft instrumentation and sondes of aerosol properties as well as from satellites (SAGE) and radiative measurements from satellites there is little if any data linking the two, especially in the tropics. Accordingly, having dropsondes on these gondolas with particle counters would provide the link between the optical depth of the cloud, its radiative properties, and its microphysical properties. This combination of experiments focused on a localized air mass can not be accomplished by satellite-based instrumentation.

Additionally, because the emission measurement will provide a reasonably accurate measurement of ozone and water vapor, the primary absorbers of infrared radiation, a full radiative heating rate calculation can be made on the air below the gondola, providing an independent determination of ascent rates in the stratosphere.

This payload would consist of Cloud LIDAR, and FTIR instruments at the gondola, both providing remote measurements of the air column below. The FTIR would take highly resolved infrared emission spectra and the LIDAR would identify the altitude and character of clouds present. Measurement of clouds at certain altitudes can be used to trigger the dropping of sondes from the gondola to measure water vapor, ozone, particle size distribution in the clouds, as well as pressure and temperature. The ozone and water vapor measurements can be used to compare with the FTIR measurements.

5.2.3 Global Radiation Balance

As part of NASA’s directive to detect long-term climate change, a simultaneous measurement of the total energy entering and leaving the atmosphere has been undertaken in an effort to determine whether the atmosphere is warming. Because this requires global coverage, the approach has been to use satellite-based radiometry to make this measurement. The program uses filter radiometers on satellites in morning, afternoon, and inclined orbits to measure the Earth’s radiation balance. However, because the satellite is in orbit at approximately 800 km, far above that part of the Earth’s atmosphere that has a significant role in radiative balance, models must be used to convert the measured radiance to a flux at the top of the atmosphere to compare with the measurement of solar flux. This conversion significantly limits the accuracy of the radiation balance determination. Additionally, the footprint of a satellite-based instrument is often too large to provide a homogeneous radiative field. Radiation measurements will often be from a mixed clear air and cloud-filled region, thus making interpretation of the data significantly more complicated.

A constellation of balloons can be used to position radiometers globally in the stratosphere for a direct radiation balance determination. This can be accomplished by positioning a pyronometer on the balloon tether. This pyronometer can be automatically flipped to alternately measure outgoing and incoming radiation to an accuracy of better than 1%, equal to the absolute radiative accuracy of the satellite instruments. The radiation must be measured from the ultraviolet (0.2 microns) through the infrared (100 microns), using filters to divide this full region into about 5 regions so that changes can be isolated to specific physical causes.

Because of the versatility provided by the tether for positioning instruments, we propose to position pyronometers at the bottom of the tether at about 20 km, and above the ozone layer at the gondola at 35 km, allowing duplicate measurements for each balloon platform. Because the ability to interpret the data is related to the effects of cloud cover, we include a cloud LIDAR instrument at the balloon gondola as well. Additionally, it is currently believed that using an FTIR would be the most accurate way to do this experiment. While it may be prohibitively expensive to plan for an FTIR on every balloon platform, this global monitoring approach lends itself to cross calibration in the infrared with one or more platforms with FTIRs specifically flying for reference measurements. Together these options show the advantages of making these measurements using a constellation of balloon-borne payloads. Figure 3 illustrates this constellation mission concept.

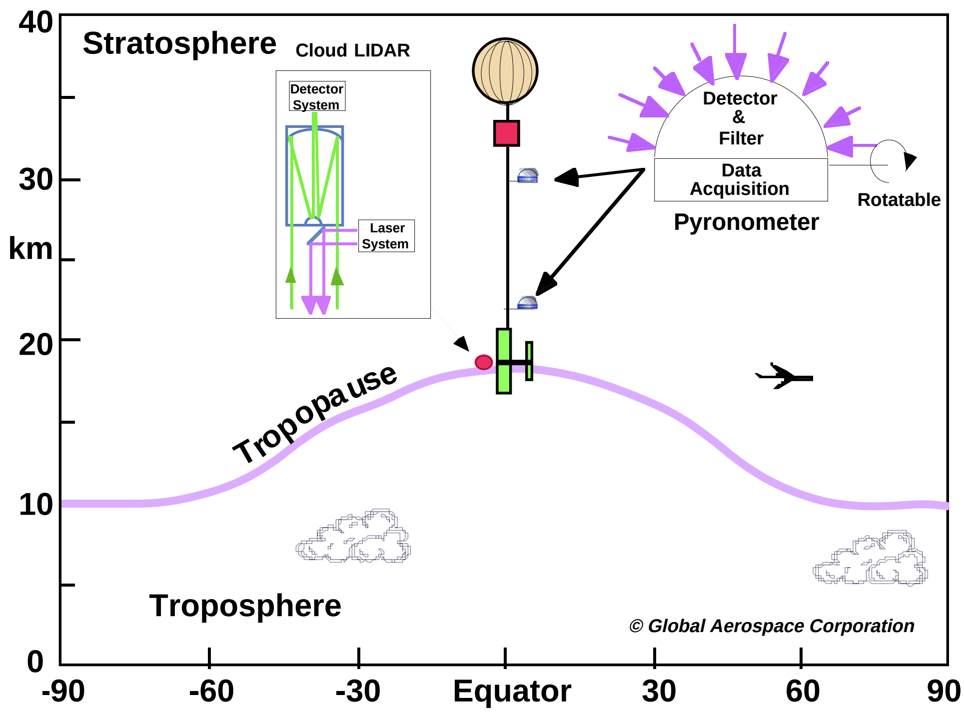

Figure 3. Climate Change: Global Radiation Balance

This experiment is consistent with the balance ESE strives to achieve in the following key areas:

- In situ observations and space-based observations needed for more complete information for calibration/validation purposes.

- A broad spectrum of Earth System Science research with a contemporary focus on climate change.

5.3 Ozone Studies

5.3.1 Mid-latitude Ozone Loss

The recent Stratospheric Processes and their Role in Climate (SPARC) report on ozone showed that during the past ten years mid-latitude ozone in the lower mid-latitude stratosphere from about 12 to 15 km has decreased by about 1%/year. Solomon et al., [1998] have postulated that in situ heterogeneous chemistry on thin cirrus could be responsible for this decline. Alternatively, transport of low ozone air from the tropics or from the polar region has also been suggested as a possibility. It has also been suggested that variability of tropopause height could be the cause. The ambiguity results from the fact that any other tracer of atmospheric transport did not accompany the ozone measurements. Because of the high resolution required by these measurements, where only measurements above the tropopause are to be considered, satellite instrumentation can not address this problem, which requires continuous monitoring. This constellation mission concept addresses a key question which is listed above as the fifth research question to be addressed by the ESE during the next several tears, namely, how and why are ozone concentrations and distributions changing?

It also responds to the part of Recommendation Three of the Pathways report, *Elucidating the links among radiation, dynamics, chemistry, and climate, as well as* Recommendation Four advocating that *Earth observations must more aggressively employ technical innovation.*

The payload, pictured in figure 2, would provide simultaneous measurements of ozone, water vapor, and nitrous oxide at intervals above the tropopause, as well as the temperature profile above and below the sail. For this payload, three highly accurate *in situ* multipass absorption instruments can be positioned at 1-km intervals above the sail, with an additional one close to the sail. A microwave temperature profiler, alternately upward and downward looking, will locate the tropopause. To provide adequate coverage for this experiment will require a minimum of 6 balloon payloads stationed in northern midlatitudes.

5.3.2 Polar Ozone Loss

Data have shown that the potential for Polar ozone depletion is prevalent and depending on the length of time the vortex holds together, how long the temperatures in the vortex are cold enough for polar stratospheric clouds to form. Ozone depletion has been observed in the Poles but quantification is difficult. Air in the vortex is continually descending and being mixed with air external to the vortex. Quantitatively understanding ozone loss requires the ability to calculate the fraction of air mixed into the vortex and what is the character of that air.

5.3.2.1 Current Plans

A NASA sponsored mission: SOLVE, utilizing balloon and aircraft instrumentation is designed to study the formation and breakup of the vortex. This type of mission requires extensive planning and relies on the ability to time the formation and breakup of the vortex. Conventional balloon-borne payloads with instruments capable of measuring the structure of the atmosphere around and in the vortex can only realistically provide measurements twice during a winter to spring period and aircraft have a limited number of missions into the vortex. Additionally, the aircraft can only reach about 20 km thus accessing only the bottom of the vortex. Two balloon payloads with proven instrumentation are planned and are listed here.

One, an *in situ* high accuracy, high precision, sub-kilometer altitude resolution payload containing the following instruments:

- JPL ALIAS II (N_2O, CH_4)
- NASA ARC Argus (N_2O, CH_4)
- Harvard University Carbon Dioxide (CO_2)
- NOAA CMDL LACE (sulfur hexafluoride (SF_6), and fluorocarbons CFC-11, CFC-12, CFC-113)
- JPL Ozone (O_3, P, and T)
- NOAA CMDL Water vapor (H_2O, P, and T)

All these instruments take data on descent, and some on ascent, thus providing 1 to 2 high-resolution profiles per launch.

Two, a remote sensing payload containing the following instruments:

JPL Mark IV solar infrared absorption provides 2 km altitude resolution and measures H_2O, CH_4, N_2O, CFC-11, CFC-12, SF_6, O_3, CO_2, CO, NO, NO_2, HNO_3, HCl, HF, CF_4.

Harvard Smithsonian FIRS-2 far-infrared spectrometer provides 2 km altitude resolution and measures O_3, N_2O, nitric acid (HNO_3), nitrogen dioxide (NO_2), nitrogen pentoxide (N_2O_5), H_2O, the hydroxyl radical (OH), and hydrochloric acid (HCl).

5.3.2.2 Proposed Constellation Concept

Balloon payloads similar to these that are deployed in the Arctic and maintain their position throughout the fall winter and spring would provide critical information during years with and without significant ozone depletion. The remote sensing payload with an FTIR making absorption measurements in the limb-scanning mode at the gondola would provide detailed information about vortex formation and breakup, transport across the boundary, and mixing of descending vortex air with mid-latitude air from below. In addition to the FTIR, a Microwave Limb Sounder would be flown. This instrument would be similar in capability to the one flown on the Upper Atmosphere Research Satellite and would specifically be used to measure reactive species responsible for ozone loss. These include chlorine monoxide (ClO), bromine monoxide (BrO), key radicals responsible for ozone destruction. The *in situ* payload would be used to quantitatively measure ozone loss in the vortex, denitrification, dehydration, and the presence of polar stratospheric clouds.

Together the two payloads would provide the means of quantitatively analyzing ozone destruction in the entire vortex.

Figure 4 illustrates the combination of payloads in and near the Arctic vortex. The remote sensing payload is as described containing the FTIR and SLS instruments at the gondola. The *in situ* payload contains instruments on the tether, positioned specifically at intervals where maximum ozone loss is expected to occur. That payload will contain two instrument suites. One a tracer suite, will measure ozone, H_2O, CH_4, N_2O, CO_2, pressure and temperature. This will provide detailed information on the transport of air in a region. The other, measuring HCl, and particles will be used to provide information on the detailed calculation of ozone loss. This payload could be used to follow an air mass to do two exciting experiments, one to monitor ozone destruction, the other to follow the formation of polar stratospheric clouds. Such a mission concept can be accomplished with constellation of 10-20 StratoSats each operating in a region from 60° to the pole.

As the previous payload, this payload would address the same key question: How and why are concentrations and distributions of ozone changing? It also responds to the part of Recommendation Three of the Pathways report, *Elucidating the links among radiation, dynamics, chemistry, and climate, as well as* Recommendation Four advocating that *Earth observations must more aggressively employ technical innovation.*

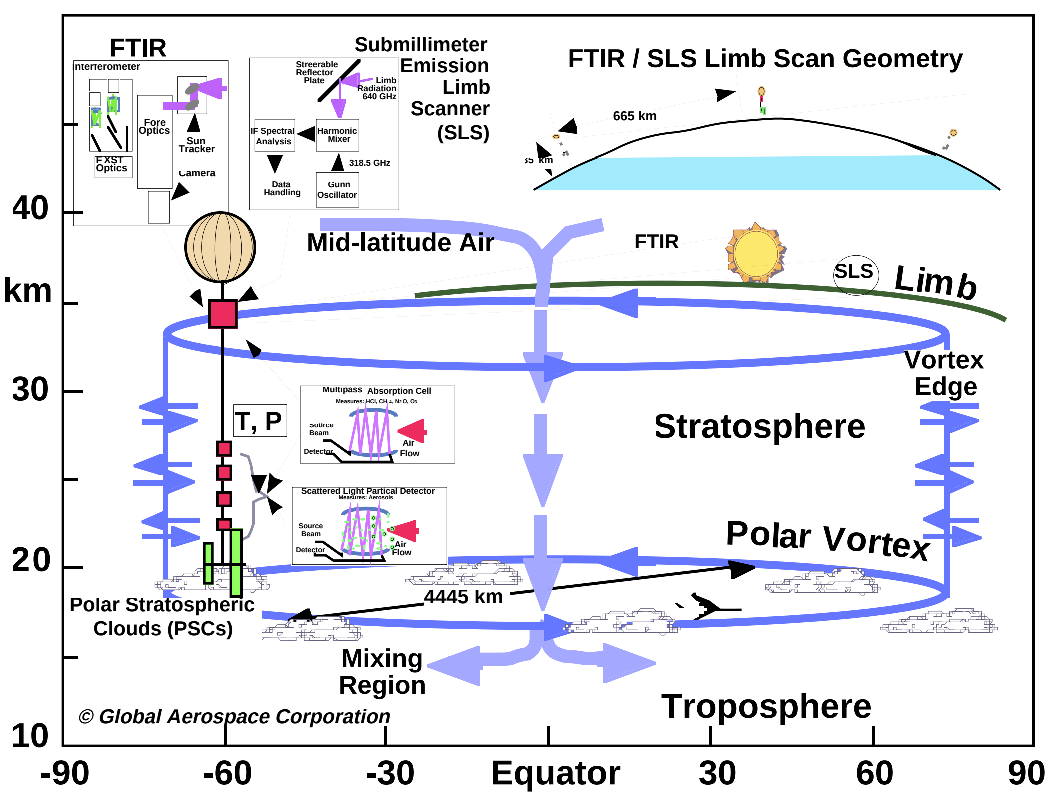

Figure 4. Ozone Studies: Polar Ozone Loss

5.3.3 Global Distribution of Ozone

This constellation concept addresses global ozone distribution; tropospheric monitoring for trends in rural areas as well as in outflow region from large emission areas; global determination of stratospheric-tropospheric exchange.

Monitoring ozone concentrations both by satellite and using ozone sondes has provided a means of determination variations or trends in ozone both in the stratospheric and in the troposphere. While satellite based instrumentation provides worldwide coverage of the stratosphere, they are of limited value in the troposphere. The sondes can only be launched from land or in special instances from ships. This means that there are large remote areas, especially in and near the tropics, where there is no coverage. There are a number of areas of research that could benefit from the measurements of ozone profiles in remote areas. In the region of the tropopause, understanding the mass flux from the stratosphere into the troposphere is required understand the sources of ozone in the troposphere. Making these measurements on a regular basis in the context of various meteorological conditions would allow for a statistical determination of this mass flux. To do this properly, it would be very valuable to simultaneously measure water vapor and temperature on the sonde. However, because these sondes would be dropped from about 35 km, the utility of adding nitrous oxide or methane to the measurement, would provide invaluable information on transport of air in the stratosphere as well. New infrared measurement techniques are currently under development which can be extended from water vapor to N_2O and/or methane and potentially result in a powerful experiment, monitoring tropospheric ozone, investigating stratospheric tropospheric exchange, and supplementing the radiosonde network, especially in the tropics where it is severely lacking. It is especially important to monitor tropospheric ozone in remote rural regions far from pollution sources because this represents a worldwide background level of pollution and is important to measure when considering the magnitude of pollution sources in urban areas. . Figure 5 illustrates this constellation and payload concept.

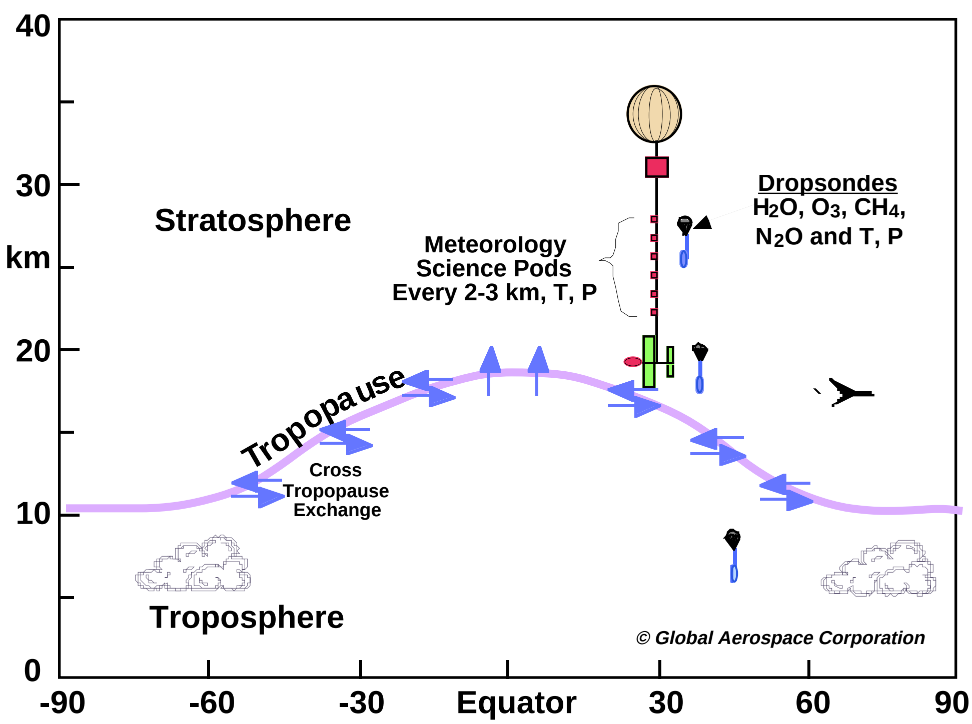

Figure 5. Ozone Studies: Global Ozone Distribution.

This payload would contain dropsondes to measure the suite of molecules described above. With the advances in technology currently being proposed for a water vapor sonde extended to ozone and methane or N_2O a sonde package of about 0.25 kg is projected. Accordingly, 400 sondes could be carried and launched at a rate of 1/day

Additionally, certain areas, whether it is the Asian continent coast of the United States, or biomass burning regions in South America, monitoring significant pollution sources it critical in understanding their contribution to global pollution levels. For monitoring these pollution sources, a nadir looking FTIR on the gondola monitoring thermal emission can provide the continuous operation necessary for this experiment, again where satellite instrumentation can not make these continuous regional tropospheric measurements. These instruments, looking at thermal emission, can make simultaneous measurements of ozone, water vapor, carbon monoxide, and nitric oxide.

This payload addresses two of the five research areas ESE has identified as the focus of effort for the next several years:

- What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?
- How and why are concentrations and distributions of ozone changing?

The experiments near the tropopause require simultaneous high-resolution measurements that are beyond the capability of satellite-based instrumentation. While satellite-based instruments designed to detect tropospheric species are planned, because of their lack of resolution and orbital characteristics they are not appropriate for continuous monitoring of localized pollution sources in the troposphere.

5.4 Hurricane Forecasting and Tracking

Disruption of life and devastation of property typically occur along the path of a hurricane. Property damage might be unavoidable, but avoiding disruption and the saving of lives can be the result of more accurate prediction of a hurricane track and its size. There are three complementary areas that need to be addressed in improving hurricane forecasting:

1. Accurate high resolution atmospheric pressure, temperature, and wind data
2. Ocean temperatures in the vicinity of the hurricane; and
3. The physics in the models that use this data for forecasting the track and growth of the hurricane.

Currently, satellites provide low resolution atmospheric data, buoys provide surface wind, pressure, air and ocean temperature, and manned aircraft fly into the storm to supplement the wind, pressure and temperature data around the storm. While this network of information has continued to improve hurricane forecasting, more high quality, high resolution *in situ* data is needed.

A constellation of balloons could be used to address this problem. Stationed in the Atlantic (and Pacific) they could carry dropsondes to measure wind, temperature and pressure in he vicinity of the hurricane. This added information would provide a significant data increase input into the models. With a projected sonde mass in ten years of 10 to 25 grams, each balloon payload could have more than 1000 sondes for this experiment. Which provide profiles from balloon altitude to the surface.

Because this balloon constellation could be useful for weather forecasting as well as hurricane tracking, there should be temperature, pressure, and horizontal wind measurements on the tether, at approximately 3 km intervals. These data could be used for input into assimilated weather forecasting models. Over the last few decades improvements in weather forecasting were limited more by computing capability than by the lack of physical data. We have reached the stage that the bottleneck for improving weather forecasting is higher resolution data. Satellite data sets have helped to fill in regions where radiosondes are lacking. However, *in situ* measurements will provide a climatology far more accurate than that given by a satellite-based system. Additionally, this network will supplement the global radiosonde network which has very limited coverage in remote areas.

This payload and its application for hurricane tracking addresses Imperative 2 of the *Atmospheric Sciences entering the 21st century: to* "Develop new observation capabilities for resolving critical variables on time and space scales relevant to forecasts of significant atmospheric phenomena." Its application to providing high resolution global atmospheric data additionally addresses the Pathways Report recommendation regarding characterizing climate change.

5.5 Global Circulation and Age of Air

All models that integrate transport and chemistry depend on their ability to model the transport of air. Currently models have difficulty with transport times in the stratosphere. Also, there are predictions that that there might be a relationship between global warming, ozone depletion, and changes in the global circulation. Monitoring the age of stratospheric air would provide significant help in understanding global change. This stratospheric monitoring on a continuous basis global circulation can be best accomplished by continuous *in situ* measurement of tracers of stratospheric transport, CO_2, N_2O, H_2O, CH_4, temperature, and pressure, at 2-3 km intervals along the tether. The most significant challenge to this experiment involves measuring CO_2 with sufficient accuracy under severe weight restrictions. This payload will require significant technical innovation to provide a calibration system adequate for the enumerated science goals. A 1-ppmv accuracy for CO_2 will provide one level of information, yielding the mean age of an air mass. A 0.1-ppmv accuracy will reveal the age spectrum of the air, meaning how old are all the individual air parcels that make up the sampled air mass. A lightweight calibration system is required for this experiment.

This experiment specifically responds to Recommendation 4 of the Pathways report that states that "the restructured national strategy for Earth observations must more aggressively employ technical innovation. Resources should be reallocated to a more agile, responsive ensemble of observations."

This payload also addresses two of the five research areas ESE has identified as the focus of effort for the next several years:

- What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?
- How and why are concentrations and distributions of ozone changing?

5.6 Global Ocean Productivity

Oceans play a critical role in the global carbon cycle, other biogeochemical cycles, and have significant potential for affecting global change. Phytoplankton help regulate the partial pressure of carbon dioxide in the water thereby affecting its air-sea exchange rate. As such, monitoring aspects of ocean properties relevant to their productivity is a valuable means of monitoring ocean changes. Satellite instruments have been developed to do this as part of the SeaWiFS (Sea-viewing Wide Field of view Sensor) project. This instrument measures ocean reflectivity in a series of visible and near infrared bands from 400 to 855 ηm to monitor ocean color and chlorophyll levels with a goal toward tracking changes in different ocean regions.

Satellite-based instruments such as this must rely on difficult calibration techniques using the sun and moon as light sources. Additionally, measurements have a large footprint meaning the data is averaged over a large potentially inhomogeneous ocean region. Furthermore, the data analysis must include an understanding of the absorption and scattering properties of the atmosphere in the field of view of the instrument. These limitations make it very difficult to validate this satellite-based data set for trend measurements.

Utilizing a constellation of balloons, visible filter radiometers, or possibly a grating spectrometer for improved resolution, similar to the aircraft-borne AVARICE instrument, positioned on the gondola could provide a data set much more straightforward to analyze. Additionally, each instrument's footprint is significantly smaller and therefore can be positioned to characterize a part of the ocean where specific questions might be of interest. For example, the impact of increasing ultraviolet radiation on ocean organisms in polar regions can be most efficiently monitored with one or more strategically positioned payloads. In another example, coastal regions, especially where there is strong interaction between rivers and the ocean waters, provide another ideal application for a balloon-borne monitoring instrument. Finally, continuous monitoring of the extent of ice cover in regions where satellite coverage is difficult or limited can be an ancillary result of this monitoring constellation, again with strategically placed balloon platforms.

The flexibility of this monitoring system allows identifying specific regions of ocean activity or potential change, and adjusting to this characteristic.

This monitoring network specifically responds to Recommendation Two of the Pathways report that states that *the observational capability be developed to support the research addressing the following critical common themes:*

- Understanding the earth's carbon and water cycles.
- Characterizing climate change.

6 Summary and conclusions

NASA has been given the responsibility through its Earth Science Enterprise to address areas of global change that are delineated above Toward this end a plan has been established using satellite-based, ground-based, and in situ instrumentation. However, the Pathways report strongly recommends a “strategy for earth observations be restructured and must be driven by key unanswered scientific questions” and “The strategy must take into account the overall balance between space-based and in situ observations.” And finally “the restructured national strategy for Earth observations must more aggressively employ technical innovation. Resources should be reallocated to a more agile, responsive ensemble of observations.” We have attempted to responded to these recommendation by describing a set of measurement concepts designed to take advantage of advanced very long duration stratospheric balloon systems which have the ability to control their global position.

The development of the balloon technology described in this report will lead to further technical advances in instrument design to take advantage of the described capability.

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