The Solar Aircraft Program Value

Questions and answers for the Centurion/Helios mission.

A Brief Description of the Atmosphere

The (1976 Standard) atmosphere is divided into five layers — the troposphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere — defined by the way the temperature of the air varies with altitude. In these layers, a gradual transition occurs from the air, as we know it, at sea level, to interplanetary space. The total mass of the air contained in our atmosphere is about one-millionth of the mass of the earth itself. A vertical column of air one-foot square exerts a pressure of a little over one ton at the earth's surface (sea level). This pressure is equivalent to our standard barometric pressure of 29.92 inches of mercury, or about 14.7 pounds per square inch. Of this atmospheric mass, roughly 3/4 is contained within the troposphere, and another 1/4 in the stratosphere and mesosphere. The thermosphere and exosphere together contain less than one-thousandth of the total mass of the atmosphere.

The effects of the atmosphere are dominated by variation in its pressure…

- Airplane pilots are required to use oxygen when flying unpressurized aircraft over half an hour above 12,500 feet.
- The highest known human community exists at about 18,000 feet in the Andes Mountains.
- The highest altitude at which the atmosphere can sustain life continuously is approximately 20,000 feet, depending on the physical condition of the individual.
- At 25,000 feet, rapid decompression will let nitrogen bubbles form in human tissues, causing the "bends".
- At 50,000 feet, the daytime sky is about ten times darker than the average at sea level.
- At 52,000 feet, it is not possible for the human lungs to ingest air, due to the evaporation of moisture from the lung tissue.
- At 55,000 feet, the power output of an un-supercharged piston engine drops to zero.

- At 63,000 feet, human blood begins to boil without a pressurization system.
- At 80,000 feet, first magnitude stars are visible in the daytime.
- At 90,000 feet, the majority of the sun's ultraviolet radiation is absorbed by ozone.
- At 400,000 feet, the daytime brightness of the sky is the same as a clear, moonlit night at sea level.
- The aurora borealis (northern lights) and aurora australis (southern lights) occur between 40 miles (210,000 feet) and 600 miles (3 million feet).

Over the last century, humans have explored the limits of our atmosphere…

- The highest known point on earth, Mount Everest, is just over 29,000 feet high.
- The highest a kite has been flown is 32,000 feet.
- The highest sailplane (unpowered) flight is 49,000 feet.
- The highest an occupied balloon has been flown is 113,500 feet.
- The highest sounding balloons have flown to 170,000 feet.
- The highest flight of a manned aircraft (other than spacecraft) was made in 1963 by NASA test pilot Joe Walker in the X-15 rocket plane, reaching an altitude of 354,000 feet at Edwards, CA.
- Satellites and spacecraft orbit the earth from 150 miles (800,000 feet) to 23,000 miles (120 million feet).

The Troposphere

In the lowest layer of the atmosphere, the **troposphere**, the temperature decreases linearly as the altitude increases. The upper boundary of the troposphere, called the tropopause (where the air temperature stops decreasing with altitude), is at about 36,000 feet at temperate (middle) latitudes, but varies from 60,000 feet near the equator down to 25,000 feet at the poles. The actual altitude of the tropopause can vary with seasons, and even day-to-day. Oddly, this variation in the tropopause altitude causes the atmosphere between 45,000 and 70,000 feet to be generally colder over the tropics than the poles.

The troposphere abounds with weather and energy. Most of the atmospheric moisture is contained within the troposphere, and, likewise, most of the pollutants contributed by natural and man-made mechanisms. The troposphere is about 78% nitrogen, and 21% molecular oxygen (as are the stratosphere and mesosphere). Other gases, such as argon, carbon dioxide, and water vapor make up the other 1% of the troposphere. Water exists in the atmosphere in gaseous, droplet, and crystalline (solid or ice) form. Also significant are particulates — such as dust, soot, and ash — and "aerosols" or tiny airborne droplets of such chemicals as sulfuric acid. Stratus and cumulus clouds predominately occur in the lower parts of the troposphere, with cumulo-nimbus, deep-vertical "storm" clouds occasionally pushing up to and penetrating the stratosphere.

The Stratosphere

Above the tropopause exists the dry, stable "desert" of our atmosphere, the **stratosphere**, which extends to an altitude of 160,000 to 170,000 feet. The composition of the stratosphere is much like that of the troposphere, except that the amount of moisture is considerably less. The stratosphere also contains a small, but significant amount of tri-atomic oxygen, called ozone. The strong absorption of solar ultraviolet radiation (UV) by this ozone layer creates a reverse temperature gradient, or inversion, where the temperature increases from an average of around -70°F at the tropopause to around freezing at the top of the stratosphere. This absorption of UV by the stratospheric ozone layer is key to our survival, because of the harmful effects this UV radiation can have on plant and animal life. The study of the human impact on the ozone layer is a dominant interest of atmospheric and environmental scientists.

Thin, wispy cirrus clouds occur in the lower part of the stratosphere, and consist of ice crystals. Occasionally, very thin, pearly-looking nacreous, or “mother-of-pearl”, clouds occur around 100,000 feet. These clouds are most easily seen from the high latitudes during the winter months when the sun, just below the horizon, is able to illuminate them from below.

The Mesosphere

The **mesosphere** extends from the top of the stratosphere to about 260,000 feet, and is marked by another decrease in temperature with altitude down to an average of about

-135°F, the coldest average temperature observed anywhere in the atmosphere. There is little ozone in this layer, and little absorption of radiation to heat the air. Extremely thin clouds, called noctilucent, occur at the upper boundary of the mesosphere, but quite rarely.

The Thermosphere

The **thermosphere** — also known as the **ionosphere** because of the presence of ionized atoms, molecules, and free electrons — also reacts with the sun's radiation, and the temperature increases from -135°F to an estimated 2000°F at 400 miles. Because the density in the upper thermosphere is so low, air temperatures there are not measured directly. The temperature can, however, be determined by observing changes in satellites' orbits caused by the drag of the atmosphere. The ionization of this layer causes radio signals to be reflected in the lower frequencies, allowing AM, HAM, and other "short-wave" radio signals to propagate beyond the curvature of the earth.

The Exosphere

The **exosphere**, which extends from about 325 miles out, has air so rarified that the molecules and atoms rarely collide, and many of these actually orbit the earth. The exosphere includes the **magnetosphere**, which extends on the sunlit side of the earth to about 40,000 miles, and on the night side to beyond the moon. This effect is caused by the earth's magnetic fields and interaction with the solar wind. Although predicted for over 30 years, it was first photographed by NASA's IMAGE spacecraft, launched just last year.

Q: What value is the Helios solar-electric aircraft program?

The Helios and its derivatives offer a completely non-polluting, self-sufficient mechanism for accessing the atmosphere up through 100,000 feet. These aircraft can provide scientific measurement of our atmosphere and persistent monitoring of the earth environment.

Ultimately, the Helios will be capable of near-eternal flight, acting as a surrogate satellite in our atmosphere at a fraction of the economic and environmental cost of space-based systems and provide more persistent and environmentally transparent "eyes in the sky" than more conventional aircraft.

Q: Why is it important to fly to 100,000 feet?

A: The most critically urgent need for data is in the regime of 70,000 to 100,000 feet in the tropics. This data will allow scientists to completely model the atmosphere, necessary for intelligent management of our environment, and allow nations to strike a critical balance between economic growth and conservation.

The stratosphere contains the ozone layer that absorbs the UV radiation from the sun. There is concern about our production of gases and other chemicals, which find their way into the stratosphere, and can destroy this protective ozone layer. Manned aircraft, such as the ER-2, have allowed us to reach up to about 70,000 feet with scientific instruments. Satellites have been able to remotely sense down to about 100,000 feet from satellites. The region between these two altitudes remains largely unsampled, except by unsystematic and infrequent balloon measurements.

There is still a need to take vertical profiles from 70,000 to 100,000 feet, particularly in the tropics, to measure key parameters. These critical parameters include water vapor and their isotopes, temperature, the radiation of heat into and out of the earth's atmosphere, so-called "greenhouse" gases (e.g., CO_2, CO, methane), photo-reactive gases such as chlorinated fluorocarbons (CFCs), particulates (e.g., soot and ash), and aerosols (e.g., sulfuric acid droplets). These measurements are essential to understanding the interaction of the sun's radiation with the troposphere and the overall radiation balance, as may be affected by the presence of an industrialized society. The solar-powered Helios uniquely offers the ability to fly through the middle stratosphere level frequently and systematically to acquire these essential measurements.

Events such as volcanic eruptions and thermonuclear explosions or accidents often push particulates up into the stratosphere. Precise and accurate data on windspeed distributions, temperature, and density in the stratosphere would support improved modeling of the transport of particulates, such as the radionuclides due to nuclear reactor accidents, like those that occurred at Chernobyl.

Q: Why don't we just ban the production of these gases and chemicals that destroy the ozone?

A: On the one hand, it is important to prevent radical changes in the environment which could destroy many life forms on earth. On the other hand, many of the people in the world are near starvation levels, and only industrial development would allow them the economic means of survival. Industrialization requires energy, and the most available forms of energy tend to have the greatest impact on our atmosphere. That is because the burning of most fuels produces carbon compounds as gases and other pollutants. These gases have a "greenhouse" effect, reducing the radiation of heat through the atmosphere back into space. The pollutants can react with and destroy stratospheric ozone, which stops most ultraviolet (UV) radiation from reaching the earth. Besides any imbalance in the heating of the earth, UV radiation can have a profound affect on all living things. Most importantly, it can kill plants that produce oxygen and food, aside from any direct harm to animals and humans from the radiation damage. An imbalance in earth’s retention of heat could adversely change weather patterns, which have been adapted to over centuries by our civilizations. Even for those not at the subsistence level of living, quality of life can only be maximized by a careful balance between economics and the environment that is based on a good understanding of cause and effect.

By developing models of the Earth system, NASA’s Earth Science Enterprise (ESE) program aims to allow intelligent compromise between economic and environmental benefits to society, by better predicting tomorrow’s impact of today’s decisions. These models require both accurate theory and frequent and systematically obtained data of the coupled atmosphere, ocean, ice, land, and biosphere system. Without data, the models cannot be calibrated or proven. Without models, the data is of no use for prediction. Without prediction, society cannot make intelligent decisions.

As an example of action that could be taken with good data and models, the 1988 Ozone (O_3) mission to the south pole detected the “smoking gun” that proved chlorofluorocarbons (CFCs) were responsible for destroying O_3. Within a year the Montreal Protocol was negotiated, and the industrial world took concrete steps to phase out CFCs. Without the models validated by irrefutable evidence from in-situ measurements, prudent governments would not commit to such an expensive industrial change. Likewise, to legislate changes in how we produce energy, which is the lifeblood of industry, we must have a very good understanding of the impact which emissions from power production have on the atmosphere. Many other human-made changes, such as the loss of forests, may have profound impacts on our quality of life that are not quantifiable without more data and better models.

Q: Why is it important to fly for months at a time?

An extreme duration aircraft allows for very low cost of operation and permits making measurements persistently. Just as watching an entire movie gives better understanding than looking at a few clips taken from it, this persistence allows for much more complete measurements and gaining a much better understanding of the environment.

The extreme duration version of Helios offers the ability to assess the dynamics and transport mechanisms that allow gases, chemicals, and particulates to move from the sources and sinks across the tropopause near the equator, which is an extremely important part of the models that scientists are trying to create for our atmosphere.

Flying extreme durations permits meteorologists to monitor developing storms off the western coasts of Africa and South America, seeing the spawning of hurricanes, and then tracking them as they grow and move across the oceans. By making measurements directly above and in the hurricanes, the prediction of the growth and path is made more accurate.

Extreme duration permits monitoring natural disaster effects, such as locating refugees, assessing access routes, and detecting disaster when normal communication with an area may be severed (such as recently happened in Honduras when Hurricane Mitch passed through). It has been reported there were over 90,000 wildfires in the western United States last year. Many of these fires were essentially un-monitored. Having a persistent "eye-in-the-sky" that could be moved over these areas to provide visual oversight and communications relay could greatly improve our resource assessment and management.

Lastly, and extreme duration aircraft, that flies slowly enough that it remain essentially in one spot while circling, can act as a "surrogate" geo-stationary satellite. Unlike the geo-stationary satellite, however, which must be about 23,000 miles above the earth to remain over one spot, the aircraft is only about 11 miles up. Also, the solar powered aircraft can fly payloads that do not need to be "space qualified", it can be relocated when required, and it can be brought down for repairs and upgrades to its payloads when desired.

Q: Why is it so hard to fly at 100,000 feet?

A: Because the air at 100,000 feet is about 75 times less dense than it is at sea level. This means we have to fly nearly nine times as fast as we do to fly at sea level with the same airplane, just to generate enough lift (because lift varies as the square of true airspeed, and inversely with density). Since we will have at least as much drag at altitude as we have at sea level, that means we will need at least nine times the power.

Q: Why did you choose solar power for the extreme-altitude mission?

Solar power increases with altitude, unlike power from fossil fuels, and it emits no pollutants whatsoever. As an added benefit, a solar powered aircraft is naturally a slow flyer.

Power from the sun is about 35% higher at 100,000 feet than at sea level. Airbreathing engines that burn fossil fuels (such as a jet or a piston engine) lose power as the air density decreases with altitude. This effect is simply because the power generated by the burning of fuel is a function of the mass of fuel that can be burned in the combustion chamber per unit of time. Because fuel and oxygen can only be burned in a limited ratio, as the density of the air goes down, there is less oxygen in the chamber to burn the fuel on each stroke (or over a unit of time for jet engines).

Solar power produces no products of combustion, not even water vapor (the principal component of jet contrails). Therefore, if very sensitive payloads are flown for atmospheric chemistry experiments, flying through its own wake while loitering on station does not present a problem.

To fly without compressibility problems at 100,000 feet, the aircraft must be large and light. A common measure of this ratio of weight and size for aircraft is called wingloading, and is calculated by dividing its mass by the projected planform of the wing. This large area, which reduces power required, also makes more space available to collect sunlight. So, once a decision was made to operate subsonically for these missions, to prevent distortion of the scientific data collected, solar power became an appropriate power source.

Q: Why can't piston or jet engines be used to reach 100,000 feet?

A: For a normal piston engine, the net horsepower output drops off a little faster than the density ratio until at about 55,000 feet, it takes all the power it can produce just to overcome its internal friction, producing no net power. A jet engine has similar limitations, although pure "turbojets" (in which all air passes through the combustor) can develop usable net thrust somewhat higher.

There are techniques and mechanisms for externally compressing air before it enters a piston engine, such as superchargers and turbochargers. For jets, flying very fast will compress the air in the inlet, before it enters the engine, increasing thrust. Jets also may have special compressors that enable higher altitude flight, but these usually must be bypassed at lowere altitudes.

Superchargers are mechanically-driven compressors of either a positive displacement or centrifugal/fan type. Turbochargers use waste energy in the exhaust to drive turbines that turn centrifugal compressors to compress the inlet air. Both of these systems were commonly used on aircraft for flights in the upper troposphere (over 20,000 feet) since the 1930's (superchargers) and WWII (turbochargers). Higher altitudes have been achieved by using multiple stages of turbocharging. However, these systems require intercoolers to take heat from the compressed air, and add greatly to the weight, drag, and complexity of the engine for flight in the stratosphere (60,000 feet and up). Also, as density of the air decreases, more stages of compression are needed to get the same power from the engine, and more and more waste heat must be removed. As the design altitude increases, larger and larger heat exchangers are needed to dump the heat into the air. Because of the increased mass and drag of the compressors and heat exchangers required, such a system becomes prohibitive above 90,000 feet.

Jet engines are similar, but can go higher, usually, before hitting RPM or engine temperature limits. Subsonic jet aircraft suffer some of the same limitations of the turbocharged piston engine, in that they need larger and larger compressors to compress the air as they go higher. Extremely fast aircraft, such as the SR-71 Blackbird spy plane, use the fast flight speed to compress the air at the inlet to the engine, and can go much higher than subsonic, air-breathing aircraft. Ram-jet engines have been designed for use on unmanned aircraft such as the Lockheed D-21, which flew a few times under classified efforts in the 1960's. Although the D-21 could fly over 90,000 feet, it required air-launching at supersonic speeds from an SR-71, or a rocket booster if launched subsonically, in order to start its Mach 3+, ramjet engine. The highest flying subsonic jet aircraft ever flown was an unmanned reconnaissance aircraft called Compass Arrow, which flew to 85,000 feet; however, it is no longer available, and its Mach 0.7 flight speed is considered very fast for environmental data collection.

The following table summarizes previous maximum altitudes for different types of propulsion systems (excluding rockets):

Propulsion System	Name of Aircraft	Maximum Altitude
Turbocharged Piston engine and propeller	Boeing Condor (UAV)	67,000 feet
Turbo-Prop	Grob Egrett	53,000 feet
Subsonic jet (ground launched)	U-2 / ER-2	>73,000 feet
Subsonic jet (air launched)	Compass Arrow (UAV)	85,000 feet
Supersonic jet (ground launched)	SR-71	85,000 feet (official) >90,000 feet (unofficial)
Supersonic ramjet (air launched)	D-21 (UAV)	>90,000 feet
Solar-electric (gnd launch)	Pathfinder Plus (UAV)	80,000 feet

Q: Why did you choose solar power for the extreme duration mission?

A: Because solar power providedes an unlimited fuel source. Although it is necessary to store energy in some type of “battery” to stay up at overnight, once this has been achieved for one day, it can be repeated again and again. The solar powered aircraft thus becomes virtually “eternal”, limited only be the wear and reliability of its moving parts.

Solar power also inherently has modest temperatures and few moving parts, also enhancing longevity. The solar powered aircraft is much like your refrigerator, which can be expected to run for up to 20 years with no maintenance, rather than your car, which requires much more maintenance.

Q: Is there a commercial use for an aircraft that flies to 100,000 feet?

A: Not directly. Most commercial use for high-altitude fliers is for performing missions like satellites do, which are some form of surveillance or communications relay. For these missions, there are diminishing returns once over 50,000 to 70,000 feet in altitude, because the higher altitudes do not increase coverage proportionately, and they diminish the ability to perform surveillance with a given sensor. Also, these commercial missions require a persistent station-keeping, which is much more achievable at the bottom of the stratosphere, just above the weather and commercial aviation.

However, much of the technology that is being developed for the extreme altitude mission will enhance the performance of the extreme duration solar aircraft that operates up to six months at altitudes of 50,000 to 70,000 feet. This extreme duration aircraft can perform many of the functions of commercial satellites at lower cost and much more flexibly.

Q: Haven't other aircraft already demonstrated flights to this altitude?

A: The only aircraft that have sustained level flight at these altitudes have been rocket powered, and flew at speeds above Mach 3 (three times the speed of sound). For instance, the X-15 flew over 350,000 feet and Mach 6 in the 60's, while exploring hypersonic flight approaching space. At these speeds, however, the shock waves and heating caused by the vehicles distort the atmospheric chemistry and prevent accurate measurement of aerosols and trace gases that are needed by scientists.

Q: What about the U-2 and the SR-71? Can't they fly high enough to get this data?

A: The U-2 (or ER-2 as currently designated for environmental research) provides very valuable missions, and does fly subsonically to high altitudes. However, the U-2 cannot fly much above 70,000 feet. This altitude was very beneficial in finding the ozone "hole" over the Antarctic, where the tropopause is much lower than at the tropics. However, near the equator, the tropopause is about twice as high, and the areas of strongest ozone absorption of UV are proportionately higher. The SR-71, of which 3 are still being flown by NASA for research, must operate supersonically when flying in the stratosphere, which distorts measurements of chemistry, and also cannot fly as high as 100,000 feet. Although the actual maximum altitude of the SR-71 is classified, its public altitude record is just over 85,000 feet.

Q: What about balloons, haven't they been used at this altitude?

A: Yes, helium-filled balloons have been used for measurements to altitudes of 150,000 feet and higher. However, there are several problems with balloons. The first is that balloons themselves leak gas and other effluents that distort atmospheric measurements of the accuracy desired (while ascending). Secondly, they cannot be controlled to sustain a particular altitude or location, but drift with the winds. Thirdly, they can only be launched in certain locations where it is safe to parachute the payloads back to earth after drifting (or else the payloads must be very small and light, such as in weather balloons). Lastly, the payloads themselves must be designed to tolerate the landing loads under a parachute. The main drawbacks to scientists are that balloons cannot offer frequent, systematic measures of the stratosphere, and cannot fly in specific geographic locations.

Q: I have heard sounding rockets have been flown to this altitude regularly, couldn't they do the same job?

A: Yes, sounding rockets do fly instruments to similar altitudes (150,000 to 200,000 feet) as the balloons above, but many of the same problems exist. Firstly, rockets can only be launched on restricted ranges. Secondly, the payloads must be rugged and fairly small. Thirdly, the payloads can persist at a given altitude regime for only a few minutes. Lastly, the rockets themselves contribute particulates and gases to the atmosphere.

Q: Isn't 100,000 feet just 25% more difficult than 80,000 feet, which you've already demonstrated with Pathfinder?

A: No. In fact, the density drops in half about every 13,000 feet in the stratosphere. The density of the atmosphere at 80,000 feet is almost 3 times greater than it is at 100,000 feet. After considering effects of Reynolds number, higher Mach number, and less stability, it is at least twice as hard to fly at 100,000 feet as 80,000 feet.

Q: What do you mean by Reynolds number?

A: Reynolds Number is a number that reflects the ratio of the inertial forces in the air to the viscous forces. The inertial forces are the main ones that provide the lift (although some small viscous effects are needed to make a wing work) and part of the drag. In a very long and thin wing, the viscous forces are the dominate part of aerodynamic drag, and also they can hurt the ability to develop lift when they get too large.

To give a physical understanding, one could imagine swimming in a pool filled with water versus one filled with molasses. In the molasses, it is difficult to push on the fluid enough to overcome its viscosity (viscosity is like friction in the fluid) and move yourself through it. Similarly, as the Reynolds number goes down, it becomes more difficult to move efficiently through the air. Lower Reynolds numbers also cause the flow to separate from an airfoil at lower angles of attack, reducing the peak lift coefficient achievable, which further increases power required.

At high altitudes, the aircraft will fly at lower Reynolds numbers than at lower altitudes (when operated at the same lift coefficient, or angle of attack). At 100,000 feet, the Reynolds number is on the order of $1/7^{th}$ what it is at sea level. This is because the Reynolds number varies directly as the true airspeed and density of the air, and inversely with the viscosity of the fluid. Viscosity of air varies with the temperature, but not significantly when compared with the change in density and speed over this range of altitudes. When an airplane flies at less than one-half that of the speed of sound through the air, Reynolds Number effects are the major concern for aerodynamic performance at high altitude. This is the case for the main wing of the Helios.

For standard airfoils, the drag coefficient can be expected to increase about 25% at 100,000 feet, and the maximum lift coefficient achievable is similarly reduced. To reduce these effects, both of which increase the power required to fly at 100,000 feet, special airfoils have been designed for the Helios and its propellers. These airfoils are intended to maximize the so-called “Laminar” flow areas on the airfoils and minimize the “Turbulent” flow areas, reducing the drag, or friction, from the air over the surface.

Low Reynolds numbers at high altitudes pose unique aerodynamic problems that must be solved in the design of high altitude, slow-flying aircraft. However these effects are small compared to the effects of reduced density and the higher speed required to provide lift.

Q: You mentioned Mach number; will Helios go faster than the speed of sound?

A: Fortunately, we will be flying at less than half the speed of sound, around 200 miles per hour. The speed of sound at this altitude is about 675 miles per hour.

Mach Number represents the flight speed as a ratio to the speed of sound. Even when aircraft do not exceed the speed of sound, the Mach number is important, because it represents the effects of compressibility of the air. Generally, when flight speed is less than one-half the speed of sound, aerodynamicists ignore these compressibility effects, and consider the atmosphere to be a “perfect” fluid, meaning one that is incompressible. Assuming an incompressible fluid greatly reduces the complexity of analysis.

When an aircraft is moving through the air at a flight speed greater than one-half the speed of sound, there may be pressure differences large enough to cause significant differences in the density of the air around the wing. When above 7/10 of the speed of sound, local accelerations of the air to move around the body and its airfoils may approach transonic or supersonic conditions, and produce a shock wave. Most commercial jet liners cruise in this regime. It requires compromise in airfoils and design techniques (such as the swept back wings seen on nearly all jet aircraft) to prevent these “Mach effects” from hurting performance or controllability.

The propellers, however, because they will be spinning as well as moving through the air, will see higher Mach number than the wing, and the performance of the propellers at low Reynolds no. and near the speed of sound is a concern. However, the Mach effects will only occur near the tips, so we do not expect the increased drag associated with transonic flow to significantly degrade performance.

Q: Why would the aircraft be less stable at high altitude than at low altitude?

The fundamental reason is that, as the fly higher and the density of the air becomes less, “wiggling” of the aircraft has less resistance from the air.

To be more specific, let’s consider the case of a more typical airplane, with a vertical and horizontal tail some distance behind its center of mass.

A stable aircraft will stay pointed in the same direction in calm air with no input from its controls. If it is disturbed, the tails will be pushed sidewise against the airflow as the aircraft rotates about its center of mass. The change in the angle of attack of the tail due to this rate of rotation will immediately create an opposing force before the aircraft has changed its angle appreciably.

This opposing force against the rotation is called “damping”. It keeps the aircraft from rotating back and forth about its center of mass, much as shock absorbers on a car stop it from bouncing on its springs after hitting a bump in the road. The amount of damping is proportional to the dynamic pressure (varies as the density times the speed squared), the distance from the center of mass to the tail, and the relative change in angle of attack — which is proportional to the rotation rate and the (again) distance to the tail, and inversely proportional to the forward flight speed.

Now, as we go higher, the dynamic pressure must remain the same, because that is what generates the lift. Consequently, the speed must go up (as the square root of the density ratio to be exact). As the speed goes up, the ratio of the sidewise velocity to the forward velocity goes down for a given rate of rotation. Since the dynamic pressure is a constant, the counterposing force caused by the rate of rotation, ie, “damping”, is proportionately less. Therefore, as we fly higher and higher, the aircraft becomes less and less damped.

Q: But the solar planes have no tail. Does this mean they have no damping?

A: Although the flying wings we have developed have no tail per se, they have similar damping characteristics. In the pitch axis (meaning the nose of the aircraft pitches up and down around this spanwise axis) there is very little tail effect. There is some pitch damping inherent from the wing airfoil itself, when it is rotated in the air. There is a little more damping from the "dihedral" or "smiley-face" shape of the wing, because it has to push the tip and center motors back and forth in the air to rotate on the pitch axis. But, most importantly, we use rate gyros to sense pitching electronically, and drive the elevators (which cover the entire trailing edge of the wing) against this pitching motion.

In the yaw axis (meaning as the wing tips swing left and right around the middle of the planform), the propellers out near the tips produce a very strong damping on this axis, as they must be sped up and slowed down to allow the wing to oscillate in yaw. In addition, we also use rate gyros in the yaw axis, to electronically command the motors to damp this lateral oscillation.

In the roll axis, which has no direct control system, we depended on aerodynamic coupling between the yaw and roll axes to stop unwanted oscillations, initially. Also, there is a lot of natural roll damping in a large span aircraft due to the wingtip going down on one side and up on the other, making rolling motions naturally hard to produce and taking a long time to develop. However, with Helios we will be experimenting with more direct feedback on the roll axis to counter any problems.

Q: Have you found stability problems in prior flights to high altitude with Pathfinder?

A: Yes, when we flew Pathfinder Plus to 80,000 feet in 1998, we discovered a roll oscillation developing as we passed through 74,000 feet. We have also seen instances of a "whirl flutter" mode of the propeller/pylons at lower altitudes, when using the large propeller blades designed for Helios.

Q: Did you have to stop climbing when this roll oscillation occurred?

A: No. It was a very slow period of oscillation, about 20 seconds, and it reached a maximum of about 8 degrees of roll angle. The pilot found he could damp the oscillation by actively making inputs in the yaw axis. We continued to climb on to the planned mission altitude of 80,000 feet.

Q: Won't this roll instability be a bigger problem at 100,000 feet?

A: No, we don't expect it to be a problem, for several reasons.

Firstly, the span of the Helios is twice that of Pathfinder plus, consequently the damping force should be about 4 times as great (remember — the distance to the tail gets multiplied by itself to determine the damping effect).

Secondly, we are going to fly with the ability to choose between an autopilot architecture which has no augmentation in the roll axis and an autopilot architecture which will allow us to use the roll rate gyro to send a yaw command to the motors, just as our pilot did manually with Pathfinder Plus.

Thirdly, the larger propeller blades and greater number of landing gear pods are expected to enhance lateral damping as well.

Lastly, as in all our flight testing, we use flight data to refine our computer simulations. We have been able to simulate the oscillations we saw in the Pathfinder with our refined models, and these same models predict a much reduced problem with the Helios at 100,000 feet than with Pathfinder at 74,000 feet, just as our deduction (above) suggests.

Q: What does "whirl flutter" mean?

A: Whirl flutter is wobbling of a spinning propeller that is caused by a resonance among gyroscopic, aerodynamic and structural forces. This is a phenomenon of propeller aircraft that occurs when a large propeller is mounted on a flexible pylon. The air loads try to push the propeller to one side. Because of its rotational speed, gyroscopic forces develop that cause the plane of the propeller to tilt in a direction off-axis to the force. The structure, acting like a spring, tries to push the propeller back to its original plane, and the result is a wobble of the propeller's plane of rotation, much like a garbage can lid that has been set spinning and is wobbling down to the ground. As the airplane flies higher, the damping goes down, just as for the roll case above, while the gyroscopic forces become larger, and the aerodynamic forces remain a constant. Thus, it is more probable to see these problems at higher altitudes than low altitudes.

Q: Was this a design flaw of Pathfinder?

A: Not really. The pylons were made flexible deliberately on Pathfinder to isolate propeller vibrations from the sensors and payloads. With the original propellers designed for Pathfinder, they were stiff enough to prevent whirl flutter. However, the Helios propellers were designed for higher altitudes and more power, and were much fatter and heavier. As a consequence, when we put them on Pathfinder for a test, the loads were too high and we saw in our video downlink while passing into the stratosphere that a whirl flutter mode was developing on some of the pylons.

Q: Won't the whirl flutter be a problem for Helios?

A: We will be looking for it, but we don't expect it for several reasons. Firstly, we learned a great deal from data we took on the Pathfinder tests, and were able to model the flutter mode we saw on video. Secondly, we incorporated changes into the pylon design of Helios to make it more resistant to flutter, and validated these changes with the computer model proven on Pathfinder. Lastly, we have heavily instrumented three of the pylons on Helios, and will be looking for indications that flutter may be developing before it is visible on the video monitor.

Appendix A — Backup for atmospheric chemistry research:

(Taken from NASA Website: http://www.earth.nasa.gov/visions/researchstrat/toc.htm,

the Earth Science Enterprise research strategy)

Atmospheric Chemistry, Aerosols and Solar Radiation

The research theme encompasses the processes responsible for the emission, uptake, transport, and chemical transformation of ozone and precursor molecules associated with its production in the troposphere and its destruction in the stratosphere, as well as the formation, properties, and transport of aerosols in the Earth's troposphere and stratosphere (the direct impact of aerosols on atmospheric radiation transfer and effects on cloud formation and properties are discussed in the subsequent chapter on the global water and energy cycle). Since variations in solar activity have considerable influence on atmospheric composition and chemistry, the monitoring of solar radiation (both total irradiance and spectrally-resolved irradiance) is also included.

Earth System Modeling

The ultimate challenge of Earth system science is to consolidate the scientific findings in the different disciplines into an integrated representation of the coupled atmosphere, ocean, ice, land and biosphere system. The hallmark of the ESE program is the integration of observations with model representations: observational data sets without an explicative model provide little insight in the nature of the underlying mechanisms; models without observation provide no verifiable conclusion. Coupled Earth system models are the tool of choice for predicting future variations and trends in the Earth system. Such models also provide tools that can be used to contribute to science-based assessments of potential future changes, both natural and forced by human influence on the environment.

Primary Forcings of the Global Earth System

The Sun is a mildly variable star that exhibits cyclical variations in its internal circulation and magnetic field, associated with minor changes in total radiation output but quite large changes in the ultraviolet part of the spectrum. Observed variations in total solar irradiance are believed to be too small to directly induce noticeable changes in the Earth's climate in the lower atmosphere. The larger variability in solar radiation at short wavelengths (UV and below) is known to affect the chemistry and composition of the stratosphere, with the magnitude of the effect increasing with altitude through the mesosphere and thermosphere. The possibility that these changes can induce sufficiently large changes in the troposphere to affect Earth's climate is a subject of active research.

Over geologic time ongoing gaseous emissions have helped determine the composition of the atmosphere. Major volcanic eruptions, on the other hand, can inject almost instantaneously very large amounts of trace gases and particulate matter directly into the Earth's troposphere, as well as trace gases into the stratosphere. Large volcanic eruptions, like that of Mt. Pinatubo in 1991, have noticeable global effects on climate and atmospheric chemistry, principally the creation of an enhanced layer of sulfate aerosols in the stratosphere which contribute to a drop in ozone levels that can persist for several years. Such volcanic eruptions constitute natural climate modification experiments: the study of the transient response to the temporarily increased burden of particulate matter is a means to gauge the sensitivity of planetary climate to forced changes in Earth radiation balance.

As human populations have grown and become more technologically advanced, they have increasingly left their mark on the Earth's environment. Human-induced changes in land cover and land use, resulting from agricultural practices, forest exploitation and clearing, grazing by domestic animals, wetland loss, urbanization, combustion, and development of industrial and transportation infrastructures, continue at a rapid pace and their effects (whether inadvertent, considered as a consequence of economic development, or deliberately made to enhance the functions of natural ecosystems) can now be seen from space over the whole Earth. In addition to the obvious disturbance of natural ecosystems, such changes may cause noticeable and widespread impacts on regional climate and hydrologic regimes, local and regional agricultural and fisheries productivity, soil erosion, sediment transport, and significant changes in land surface albedo and aerodynamic roughness, as well as changes in the biogeochemical cycling of carbon, nitrogen and other important elements. The implications of these changes for sustainable food production and resource management as well as the maintenance of a healthy, productive environment are a very serious concern for societies.

In recent times, however, the most significant anthropogenic forcing of the planetary environment has been the modification of the composition of the atmosphere, leading to rising concentrations of a number of reactive and radiation absorbing gases that contribute to depleting the stratospheric ozone layer and to increasing the atmospheric greenhouse effect. Measurements at the Mauna Loa observatory and several other stations have documented a recent upward trend of about 0.4% per year in atmospheric carbon dioxide (CO2), amounting to a 30% increase in global atmospheric concentration since the beginning of the industrial era. The buildup of atmospheric CO2, driven by the combustion of fossil fuels along with deforestation and other changes in land use, is the largest contributor to the global increase in the greenhouse effect. Quantifying the fraction of CO2 from anthropogenic sources that accumulates and remains in the atmosphere (about half of total emission) is, in itself, a very complex problem, considering that CO2 fluxes from the combustion of fossil fuels and changes in land use are but a small fraction of the large natural fluxes between atmospheric, terrestrial ecosystem, and oceanic reservoirs. However, since the natural processes have been "in balance" even seemingly small perturbations in the sources and sinks due to human activity can lead to significant changes in atmospheric CO2 levels.

Many human enterprises, from natural gas extraction to animal husbandry and the intensive cultivation of rice, generate yet poorly quantified amounts of methane. Methane gas in the atmosphere is more effective on a per molecule basis at absorbing infrared terrestrial radiation than CO2. Thus, the oxidation of methane at the source or subsequently in the atmosphere effectively reduces the overall impact on the greenhouse effect. Many other trace gases produced by human industry, such as the by-products of fertilizer usage, chemical pollution from internal combustion engines, or the purposeful synthesis of special chemicals by industry (e. g. chlorofluorocarbon compounds) also add to the overall greenhouse gas burden. Ozone, sensitive to a variety industry-produced compounds, also plays multiple climate forcing roles, through the absorption of solar ultra-violet radiation and terrestrial infrared radiation. The increase in tropospheric ozone over much of the world as a result of industrial activity has led to the contribution of ozone to radiative forcing being sufficiently important that it must be included in studies of climate forcing.

Another important forcing of climate is caused by natural and anthropogenic aerosols in the troposphere. The tropospheric aerosols produce a direct radiative forcing by virtue of scattering and absorbing solar radiation and an indirect forcing by changing the radiative properties of clouds. Radiative balance calculations suggest that the aerosol climate forcing can be comparable in magnitude but opposite in sign to that of anthropogenic greenhouse gases. However, the exact magnitude of the total aerosol forcing remains one of the largest unknown factors in climate research. It has even been speculated that the negative forcing of climate may have offset to a large degree the positive forcing due to the greenhouse gases, thereby temporarily masking much of the anthropogenic greenhouse effect.

Fires can effect large-scale, sometimes catastrophic, changes in land cover and terrestrial ecosystems, while creating large amounts of volatile pyrogenic materials, such as carbonaceous compounds and soot, that can disperse over very large atmospheric volumes and cause significant changes in the composition of the atmosphere and its radiative balance. The generation of fires and their ability to spread depends on climatological, ecological, and human factors (especially land use management). Fires also release trace gases and particulate matter into the atmosphere that can modify atmospheric chemistry and contribute to the greenhouse effect. Biogeochemical cycling in terrestrial ecosystems is profoundly affected by fires; nutrients can be made more available by fire and its after-effects on soils, they can be lost to the atmosphere in the form or trace gases or particulate matter, or they can be transported and deposited to distant ecosystems (both terrestrial and marine).

Responses of the Earth System to Natural and Human-induced Disturbances

From a planet-wide perspective, observation shows that the primary indicators of the state of the Earth system vary from year to year and continue to evolve over periods of decades and longer. Long-term trends, in addition to inter-annual variations, are observed in the global atmospheric composition and circulation, Earth surface temperature, the global water cycle and total rainfall, the duration, frequency and severity of weather and hydrological phenomena, the ocean circulation and distribution of ice on Earth, global carbon cycle and total carbon storage in the Earth's oceans and terrestrial biosphere, the distribution and extent of global land cover, and the thickness of the global ozone layer. Establishing the existence of such trends against the background of geographic differences and transient fluctuations is a technical challenge, requiring full use of the resources (precision and global coverage) of modern observing techniques. In this regard, satellite observations have given us a powerful means to collect the required information systematically, globally, and under fully traceable conditions (notably, consistent sensor calibration).

The problem remains, however, of attributing the observed changes and trends to individual or combinations of causal (forcing) factors. The answer to this problem lies one step deeper in the basic physical, chemical, geological, biological, and social processes that control these planetary-scale changes and long-term trends. The basic processes are often mutually reinforcing or, to the contrary, restraining, and combine to constitute feedback mechanisms that amplify or moderate the response to primary disturbances and forcings.

Prominent among these mechanisms are the coupled variations in atmospheric temperature, water vapor, and clouds that govern radiation transfer through the atmosphere and changes in the global radiant energy budget of the planet. A rise in temperature is accompanied by an increase in atmospheric water vapor and its contribution to the greenhouse effect, thereby amplifying the primary forcing that caused the elevation of temperature in the first place. The role of clouds is much more complex, as different types of clouds can induce opposite net effects on the planetary radiation budget. The principal effect of low-lying, dense, and very bright water clouds is to cool the atmosphere by reducing the amount of solar radiation absorbed by the planet, whereas the presence of relatively thin and semi-transparent ice clouds at high-altitude primarily enhances the absorption of terrestrial infrared radiation and warms up the lower atmosphere. Also important is the role of clouds in moistening and/or drying the upper troposphere, as water vapor in that region of the atmosphere, has a potentially large, but incompletely understood, impact on the greenhouse effect and climate.

The formation of clouds is closely associated with the development of weather systems; purely dynamical changes in atmospheric flow will influence the distribution of cloudiness, the radiative balance of the planet, and rainfall distribution, even without any obvious change in global mean atmospheric temperature or humidity. Much improved knowledge of basic cloud processes and the life cycle of cloud systems is needed to predict how clouds might change in the future as a result of change in the atmospheric circulation and thermal structure. In general, a fundamental objective is the understanding of the relationship between climate change and the frequency/intensity of weather disturbances, which play a disproportionately large role in atmospheric transport and mixing, cloud system development, energy transformation, and precipitation.

The health and primary productivity of marine and terrestrial ecosystems are sensitive to changes in climatic conditions as well as the availability of nutrients and other environmental controls. Productivity is governed by the amount of incident solar radiation, the availability of water and atmospheric carbon dioxide; the stability of temperature within the relatively narrow range suitable for life; and the availability of required nutrients in terrestrial soils, brought from the deep by ocean upwelling, or transported by the atmosphere from another region of the Earth. The primary productivity of the biosphere is one of the principal processes governing the Earth's carbon cycle on annual to decadal time-scales. The changing phenological state and health of plants likewise govern the rate of exchange of CO2 and water between the atmosphere and vegetation, thus controlling, at the same time, the storage of carbon and the loss of water by terrestrial vegetation. In this respect, vegetation plays a major (moderating) role in the hydrological cycle, surface water storage, run-off, infiltration, and regional hydrologic regimes in general. Similarly, in the ocean, phytoplankton.contribute significantly to spatial variations in CO2.

From an Earth system perspective, the global carbon cycle is governed by the global distribution of marine and terrestrial ecosystems and the impact of their biological activity on the global environment. In particular, it is essential to relate the intensity of biological activity to the controlling (radiative, meteorological, hydrological, biogeochemical) factors on a global basis, including the cycling of other chemical elements (e.g., nitrogen) that are critical to the development and functioning of ecosystems.. Remote sensing provides the opportunity to gather much of the needed global data on both the distribution of ecosystems and relevant forcing factors, but converting these observations to information on global environmental impact requires sufficient knowledge about basic processes and the function of ecosystems. Process-level knowledge is acquired primarily through *in situ* studies, often in the context of major field campaigns which allow detailedanalysis of key processes and controlling factors.

Likewise, it is essential to understand the global water cycle, both as the central element of atmospheric climate change and a critical environmental factor that influences the other components of the Earth system. In particular, the availability of soil moisture and the transition of frozen soil to thawed conditions have a controlling influence on the productivity of terrestrial ecosystems. Conversely, the phenological progression of vegetation from dormant, to growing, to mature stages, governs the ability of vegetation to draw water from the ground, transfer it to the atmosphere, and thereby influence surface climate and the partitioning of radiant energy between latent and sensible fluxes. The global measurement of soil moisture, snow-water equivalent, freeze-thaw transitions, stage of water in rivers and inland water bodies, and river flow could significantly enhance our knowledge of the global water cycle..

It has been shown beyond doubt that halogenated compounds produced by human industry are the primary cause of global decline in the amount of stratospheric ozone. This includes both the decreases in global ozone amounts and the much larger decreases in high latitude spring observed in the Antarctic and, to a lesser extent, in the Arctic region.. The phenomenon is governed by the complex chemistry of atmospheric ozone, involving numerous chemical species and free radicals, and controlled by climatic conditions that allow very low temperature to form and persist for long periods of time. Conversely, the distribution of ozone and some other absorbing molecules control radiative heating and stratospheric climate (circulation and temperature).

This linkage between chemistry and climate provides opportunities for complex and non-linear interactions. Most importantly, low stratospheric temperatures permit the formation of cloud and aerosol particles, which can have significant implications for both atmospheric chemistry and for radiation. Detailed understanding of the conditions under which these particles form is important if accurate forecasts can be made in an atmosphere with altered temperature distributions. Similarly, changes in the dynamics of the tropopause region could affect the transport of water vapor and other trace gases from the troposphere into the stratosphere and thus affect aerosol formation, chemistry, and radiation in the stratosphere. Understanding how stratospheric water vapor might change in the future requires basic understanding of the dynamics of the tropopause region and troposphere-stratosphere exchange mechanisms. Finally, any change in meteorological activity that drives the stratosphere and affects the stability of the polar vortices will have significant impacts on chemistry, especially the partitioning of chlorine and nitrogen between compounds which are more and less active in ozone depletion. Conversely, atmospheric model simulations show that changes in stratospheric circulation and thermal structure may propagate downwards and affect tropospheric climate. The factors that control the stability of the polar vortices and their relationship with tropospheric circulation must be understood to assess the implications of possible future variations.

Microphysical and chemical processes, as well as atmospheric transport, mixing, and removal, govern the formation of aerosols in the lower troposphere from a variety of surface sources and/or precursor gases, their number and size distribution in the atmosphere, their composition and optical properties, and ultimately their direct effect on the planetary radiation balance. Satellite observations provide the potential to help characterize the global distribution and, to some extent, the properties of aerosol particles in the atmosphere. However, variability in aerosol types, height, chemical composition and optical properties means that satellite observations alone cannot provide all the needed information on aerosols. A variety of observational data from *in situ* sampling, airborne and ground-based optical remote sensing, advanced satellite instruments, and detailed modeling studies of aerosol processes will be needed to understand the relationship between aerosol composition, height distribution, and optical properties under a sufficiently broad range of aerosol types and geophysical conditions. Even more complex cloud-dynamical and microphysical phenomena are initiated by aerosol condensation nuclei which may induce significant changes in the particle size distribution of low-lying clouds and cause indirect climate forcing by altering the optical properties of these clouds. Sufficiently detailed knowledge of the processes by which aerosols affect cloud formation and properties must be obtained on a global scale so that these indirect effects can be realistically represented in models.

The formation, transport and eventual melting of sea-ice at high latitude involve complex ice and water properties, polar weather phenomena, and the oceanic circulation. Over 10-13% of the surface of the ocean, sea-ice acts as an insulating layer that blocks exchanges of water and energy with the atmosphere. The high albedo of raw and snow-covered ice further reduces the absorption of solar radiation and tends to maintain the surface cold, with direct consequences on polar atmosphere stability and weather. The formation of sea-ice is accompanied by the rejection of concentrated brine that increases the salt content of the ocean locally and promotes the sinking of cold, high-salinity surface water to great depth. Conversely, the advection and melting of relatively fresh sea ice lowers the salinity of the ocean and blocks deep water formation, thus inducing a complex coupling between sea ice, deep water formation, and decadal climate variability. The measurement of ocean surface salinity can dramatically increase our knowledge of the conditioning of ocean waters by air-sea interactions and their impact on deep-water formation.

Consequences of Changes in the Earth System for Human Societies

Statistically meaningful but small changes in the global distribution of Earth system properties, such as mean surface temperature or sea-level pressure, would not draw much attention if we did not foresee that relatively small variations in the global environment can entail changes of much greater significance in regional weather, productivity patterns, water resource availability, and other environmental attributes. We already know, for example, that La Niña climate episodes, manifested by cooling of surface waters in the eastern tropical Pacific ocean by a few degrees Celsius, are associated with more active hurricane seasons in the Atlantic basin, featuring more frequent and generally stronger tropical cyclones than normal years. Conversely, El Niño warm ocean water episodes have dramatic impacts on regional marine productivity and broader climate patterns, including the frequency of Atlantic hurricanes.

There is little doubt that other global climate changes can also induce significant differences in the frequency, duration and intensity of weather disturbances, such as severe storms and rainfall, floods and droughts. In particular, the acceleration of the global water cycle due to warmer temperatures is expected to produce heavier rains and larger water run-off, especially in winter, but also faster evaporation and generally drier conditions in summer, thus amplifying the contrasts between dry and wet seasons, and exacerbating chronic water shortfalls in arid regions. Global climate warming observed during the last few decades appears to have already resulted in a lengthening of the growing season at mid- to high-northern latitudes, and may be contributing to desertification in the sub-tropics (IPCC, 1998). Changes from snowfall to rainfall would also significantly affect the annual patterns of stream flow (higher in winter, earlier peak flow, lower summer flows), which can have dramatic impacts on fisheries as well as irrigation needs.

Sea-level rise, resulting from the thermal expansion of ocean waters and mass loss from continental glaciers and ice sheets, is a gradual but important phenomenon of concern to all coastal countries, especially low-lying atolls. Sea level rise is accompanied by a redistribution of coastal materials, beach erosion, flooding of freshwater wetlands and the invasion of coastal aquifers by salt water. The societal implications of sea level rise are significant. It is estimated that a 0.5 m rise in sea level would cause a loss of about a third of US wetlands (with corresponding loss of the biogeochemical recycling capability and ecosystem goods and services, such as fishery productivity, from such wetlands.

Ecosystems may have difficulty adapting to relatively rapid changes in the physical environment. Climate change is thus becoming an additional stress that may combine with other stresses, e. g. invasion by exotic species or increased frequency and/or extent of fires, to alter drastically the structure and composition of established ecosystems and lead to their impoverishment or ultimate disappearance in favor of a more tolerant ecosystem. An example of a particularly sensitive ecosystem that cannot easily "migrate" to a more favorable region is that of tropical corals, now subject to bleaching and death almost everywhere. Deforestation and other ecosystem disturbances caused by human activities can result in irreversible changes, such as loss of species (biodiversity), and other undesirable effects such as increased erosion, loss of essential nutrients, decreased agricultural productivity, and accelerated rainwater runoff from watersheds. It is vitally important to understand the consequences of such changes for sustained agriculture, forestry, and fisheries and the continued provision of ecosystem goods and services that are valuable to human societies. It will be especially important to understand the controlling factors when sustainable production is successfully achieved while the ecosystem is under pressure from population growth and/or land use change

Prediction of Future Changes in the Earth Climate and Global Environment

The overarching purpose of Earth system science is to develop the knowledge basis for predicting future changes in the coupled physical, chemical, geological, biological, and social state of the Earth and assessing the risks associated with such changes. Of particular interest are changes in physical climate on the time scale of a human generation, e. g. changes in the composition and chemistry of the atmosphere, and changes in biogeochemical cycles and primary productivity. It is clear that to predict the long-term evolution of the Earth system, a good understanding of the way that humans will interact with the environment must be obtained and represented in the models used for simulations.

A first step towards predicting the future of the Earth system is building a capability to simulate realistically the present state and short-term variations of the global environment. This includes defining accurate and realistic representations of all relevant forcing factors and their role in the system, and the physical, chemical, geological, and biological processes involved, including especially the processes which couple the different components of the system: the global atmosphere; the world oceans; land and sea ice; marine and terrestrial ecosystems; and the Earth's landscapes and surface geology. The only practical strategy for such a complex task is to develop predictive skills, focusing necessarily on suitably defined sub-systems of the complete Earth system for verification against observations.

Frequent experimental data assimilation and prediction cycles, made possible by the daily acquisition of global atmospheric, oceanic, and surface observations, are instrumental in verifying and improving the representation (prediction) of realistic weather and weather-related phenomena in climate models. On longer time scales, realistic representation of atmosphere-land hydrology and atmosphere-ocean interactions, as well as the full three-dimensional nature of the ocean, become essential. Experimental predictions of significant interannual climate fluctuations, for example ENSO phenomena clearly require information on the physical state of the oceans. Simulation of transport, mixing and transformations of trace gases and aerosols in the Earth’s atmosphere is an attractive proposition whenever suitable environmental and meteorological data are available to verify model predictions. Predictions based on atmospheric chemistry or biogeochemical cycling models may be tested against the current distributions of relevant compounds in the Earth's atmosphere, oceans, land, and biosphere. Ecological research is striving to acquire the same type of information on marine and terrestrial ecosystem dynamics to test model simulations of the recovery of these ecosystems from known disturbances or stresses.

Predictive models can similarly be used in a retrospective mode to simulate past changes for the purpose of testing hypotheses about the possible causes of these changes and verifying the models' capability to reproduce the full range of observed variability. The latter is especially important to gauge our capability to assess the risk for rapid changes and possible surprises in the evolution of the Earth system. The use of mathematical analogs to simulate past changes, that are documented directly in the historical record or indirectly by various existing paleoclimatic indicators, is also a powerful means to identify key linkages between the components of the Earth system.

The objective, however, is to build on the confidence gained in simulating current or past environmental conditions and apply these skills to the prediction of future long-term changes. Such predictions are usually intended to assess the potential consequences of various assumed scenarios for the future evolution of relevant forcing factors: emissions of active chemical compounds and greenhouse gases from various sources, changes in the global cycles of carbon, nitrogen, and other important elements, changes in land use and water management, population growth, economic development, etc. It is important that the modeling tools used for prediction have the capability, including spatial resolution, needed to address regional impacts of predicted global changes.