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REDEFINING SNOWSTORMS

A-TRAIN SATELLITE PLAN

HUGE, SPIKY HAILSTONES



WATCHING CLIMATE
LIKE A HAWK

A GLOBAL PROFILING STRATEGY

A GLOBAL PROFILING SYSTEM FOR IMPROVED WEATHER AND CLIMATE PREDICTION

BY ALEXANDER E. MACDONALD

Unmanned aerial vehicles and moored ocean buoys could track long-term climate change, and provide weather and climate models with the profiles they need of state and forcing from the stratosphere to the deep ocean.

New *global observing possibilities*. Recently, it has become technologically feasible to take routine, detailed vertical profile measurements of the atmosphere and ocean at a large number of fixed points over the globe. If combined with land stations on the same extended grid, it would allow a global, spatially unbiased network for climate monitoring and weather prediction. In the atmosphere, such a system could use a new generation of high-altitude long-endurance (HALE) unmanned aerial vehicles (UAVs) that could routinely cruise in the lower stratosphere (flight level 60,000 ft, 20 km), dropping sondes to measure state variables (temperature, wind, and water vapor), and occasionally descend to near the surface (150 m) to measure other

parameters such as cloud droplet spectra, aerosols, trace gases, and carbon dioxide isotope ratios. In the ocean, at the same locations where the atmospheric profiles are measured, new buoys similar to those used in the Tropical Atmosphere–Ocean (TAO) array of the tropical Pacific could be deployed. These buoys would be a new generation of less expensive and more capable moorings that would allow profiles of temperature, salinity, and current into the deep ocean. Figure 1 shows a hypothetical network of locations consisting of 240 points over the Earth’s oceans and polar regions, which could comprise a baseline “Eulerian” (i.e., measurements at fixed points through time) observing system. This sample network of points is taken from a global icosahedral grid with 362 points, each centrally located in a 1.4 million km² domain. The optimal distribution of the proposed network would need extensive study. Ideally, the ocean and polar network would be complemented with a land-based network that is similar to that discussed in WMO (2004), resulting in coverage for the entire globe. Dropsondes that could take soundings of the high absolute accuracy that is needed for climate monitoring would be taken once every 3 days. By measuring oceanic and atmospheric

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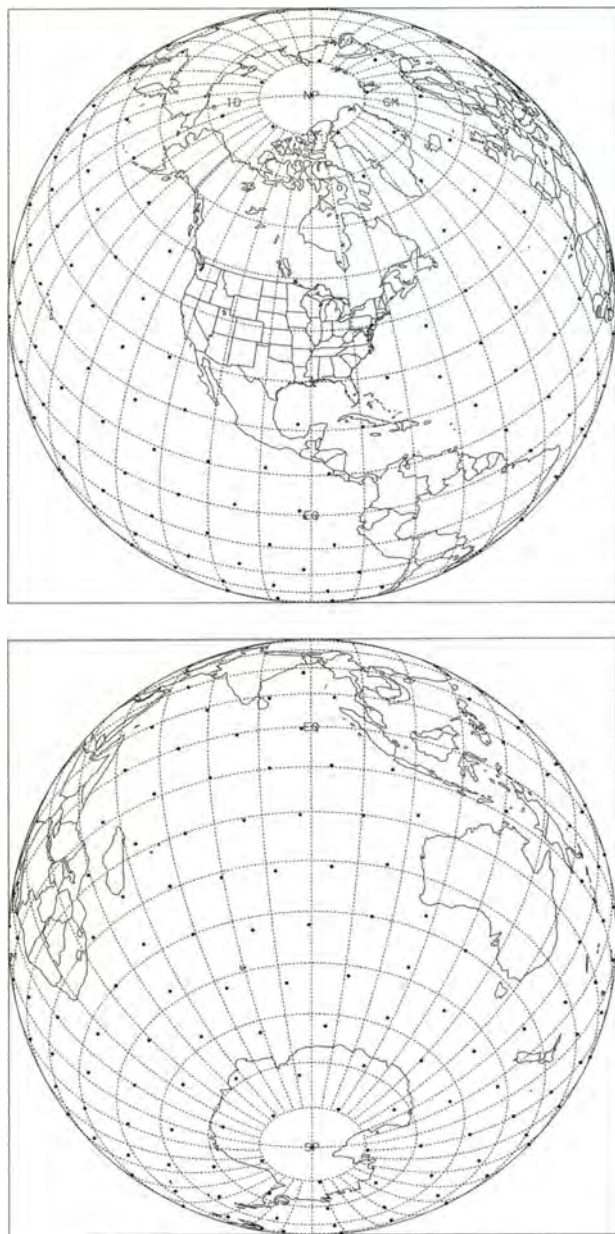


FIG. 1. Proposed “climate” observing points, consisting of 240 locations covering the oceans and polar regions. By using an icosahedral grid, each point represents approximately the same geographic area, about 1.4 million km².

profiles at the same geographic points, the interaction between the ocean and atmosphere could be monitored as it changes (or not) through the remainder of the century.

Purpose of the global profiling network. The primary objective of such a long-term operational network would be to improve weather and climate prediction, including better forecasts of hazardous weather, such as tropical storms and midlatitude cyclones. It is likely

that long-term, anthropogenically forced climate change will be a dominant issue for the twenty-first century (Houghton et al. 2001). The potentially dire consequences of increasing greenhouse gases (particularly carbon dioxide, because of its long lifetime in the atmosphere and ocean) will have to be judged against the immense cost that the reduction of fossil fuel consumption would entail. Serious inadequacies in the current and planned global observing system could cause policy decisions to be made in the coming decades with much less certainty than the gravity of the situation dictates.

A global, spatially unbiased network (the proposed network complemented by a land-based network) would address one of the most important issues of long-term global change—the potential for abrupt regional climate changes (NAS 2002). Regional climate change could be very damaging ecologically (e.g., in the Arctic) or economically (e.g., impacts of midcontinent dryness on global food production; MacDonald 2001). Although there is an understandable focus of long-term climate change on average global temperature rise, less attention has been paid to regional climate change and the ability to detect it early. Our lack of certainty concerning regional climate changes dictates that the observing system should be designed to detect them no matter where they begin.

Importance of profile time series. The proposed system could supply vertically detailed observations at points that are representative of 70% of the globe, where such measurements are currently very sparse. It would significantly improve the monitoring of crucial climate state variables and associated feedbacks, such as the increase in upper-tropospheric water vapor expected as a result of anthropogenic effects, as well as changes in the temperature and moisture over the Arctic Ocean. It could provide quantitative measurements of cloud droplet spectra, aerosol size distribution, chemical constituents, and radiative forcing throughout the vertical column (Fig. 2). Observations of the vertical energy exchanges in each column (e.g., instruments that measure radiation flux divergence) would allow the calculation of vertical energy balances, which can be related to observed changes of state variables (i.e., temperature, water vapor, wind, and pressure). It is argued below that detailed globally representative profiles of state and forcing (e.g., heating) parameters are necessary for the development of credible long-term climate models.

There are other compelling scientific reasons to take long-term observational profiles at fixed points. An accurate time series that includes time scales from

days to decades can reveal the frequency distribution of different variables, which is information that reveals much about physical behavior that cannot be obtained in any other way (Tuck et al. 2004). The proposed network would measure many oceanic and atmospheric properties, providing a way to link their related physical behavior in the same place. The instruments on board the UAV can be tested and recalibrated before every flight, which makes them ideal for the continuous calibration of instruments such as satellite remote sensors and drifting buoys, which are more difficult to service directly.

Complementarity to the integrated global observing system. A recently inaugurated program (Clery 2005), called the Global Earth Observing System of Systems (GEOSS), emphasizes international cooperation and planning for observing systems that are being deployed by various nations to make them mutually useful, accessible, and supportive of overarching societal goals. GEOSS includes an effort to better use existing observations, with a plan to identify gaps in the existing global system. Although some have argued that the needed global observing system is simply a matter of more effectively using the existing and planned global observations, the argument made here is that the global system is missing an essential “profiling” component, like an automobile that has everything but wheels.

The proposed system enters an arena with many existing and potential observing systems. A rich and diverse set of satellite observing systems, including polar-orbiting microwave receivers, infrared spectrometers (Smith 1991), lidars, global positioning system (GPS) sounders (Kuo et al. 2000), and ocean

surface scanners exist in various stages of development and operations. Typically, satellite sensors, located hundreds or thousands of kilometers from the fluids that they are measuring, are horizontally comprehensive, but have various deficiencies. For example, infrared interferometers that are becoming available on satellite platforms can provide high vertical resolution, but only above clouds, limiting their value for climate trends. Microwave sounders can see through clouds, but have relatively low vertical resolution, and have been problematic for use in climate trends; different studies come up with significantly different temperature trends using the same data (Christy et al. 2000; Wentz and Schabel 2000; NAS 2000).

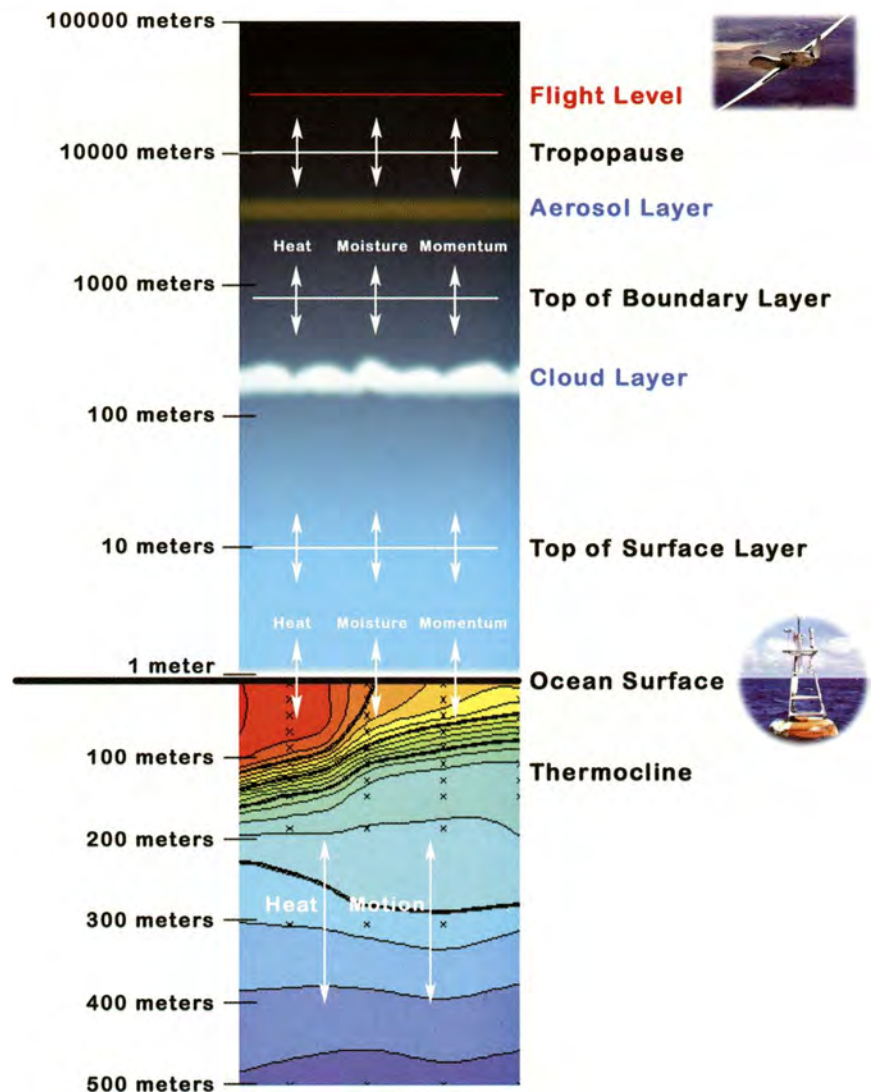


FIG. 2. A key attribute of the network is its capability to determine the details of state variables, forcing (e.g., from aerosols and clouds), and radiation for the coupled ocean and atmosphere. This would allow for the estimation of vertical energy balances, including all major processes.

Recent U.S. National Academy of Science studies have emphasized the imperative for long-term observational strategies and the importance of an *overall design* of the global observing system (NAS 1999), such that the composite system is optimized for its intended uses. The complete system can be thought of as concentric tiers, with the surface and subsurface comprising tier zero, air vehicles as tier one, polar-orbiting satellites as tier two, and geostationary satellites as tier three (Fig. 3). The four tiers each provide complementary coverage of the Earth. For example, a constellation of five geostationary satellites can obtain frequent images of a large part of the Earth, while a constellation of polar-orbiting satellites has advantages (mainly because of being closer to the Earth) for atmospheric sounding. The operations

concept for keeping 12 aircraft continuously in the stratosphere would have access to each of the designated points once every 72 h; they can be thought of as a constellation of “stratospheric satellites,” with unique capabilities that are complementary to those in the other three tiers.

It has been shown that three-dimensional fields of temperature and moisture can be recovered more accurately by an analysis that includes both satellite radiometric data and in situ soundings than by either one in isolation [e.g., the Kalman filter analysis of Fleming (1998)]. Aerosols are an example of how profiles from the UAVs could be combined with satellite data to deliver an excellent field for use in radiation calculations. Figure 4 shows two Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite images of

Saharan dust as it is carried over the Atlantic Ocean. The cloud appears thicker on 26 February 2000 than it does 2 days later. However, a detailed and accurate radiation calculation would also require the size spectrum of the particles as distributed in the vertical direction. Multispectral measurements from satellites, calibrated by actual particle size distributions from onboard instrument profiles, would allow a full three-dimensional characterization of the aerosol cloud; neither platform by itself will be able to adequately characterize the volume radiation effects of aerosols. Similarly, as discussed in Houghton et al. (2001, p. 221, Fig. 12.5), a big uncertainty in global change calculations is the effect of anthropogenic aerosols, acting as cloud condensation nuclei, to change cloud droplet spectra and cloud radiation. In situ measurements of cloud droplet spectra and anthropogenic aerosols that are available from the profiles would reduce the range of uncertainty.

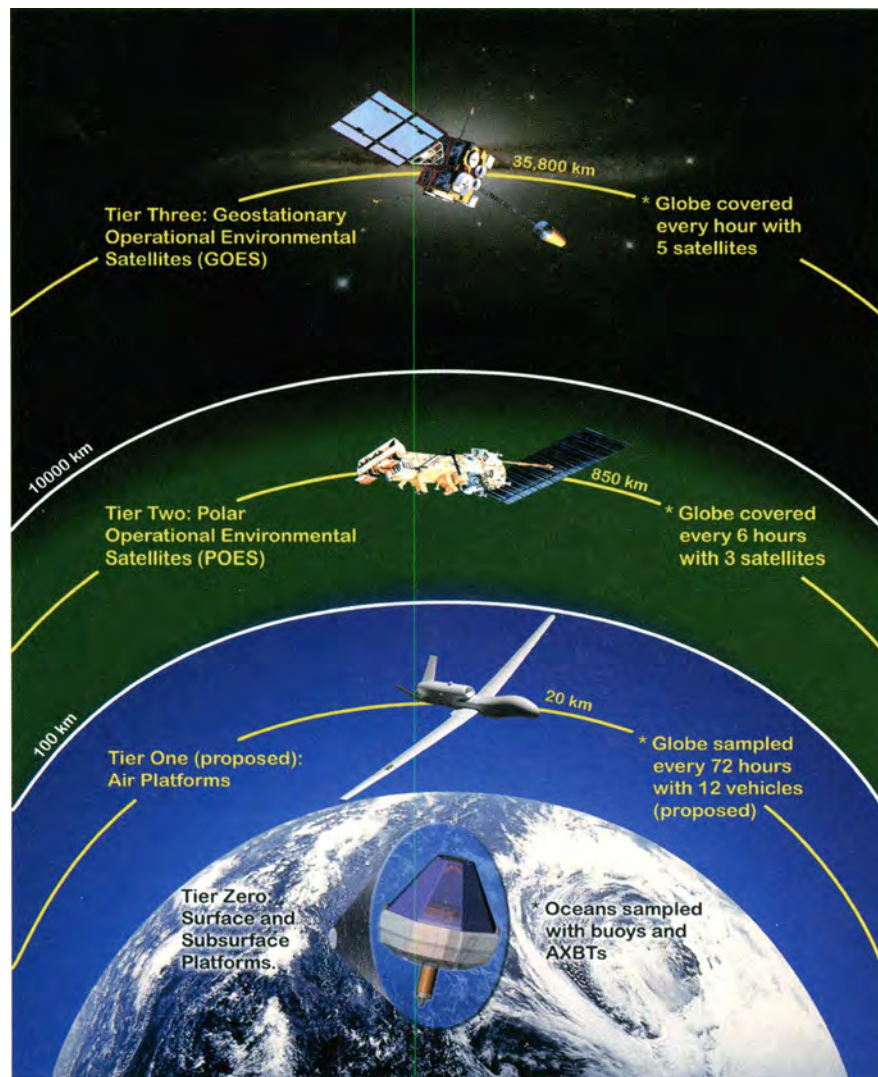


Fig. 3. An operational Earth observing system for the twenty-first century. The design of the optimum system for weather and climate prediction requires consideration of all tiers as part of a single system.

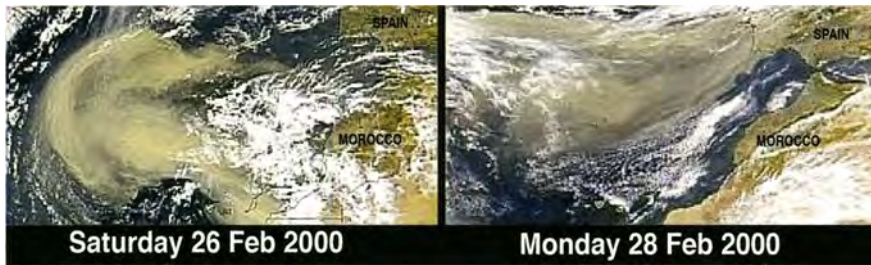


FIG. 4. Dust from a Sahara desert dust storm is carried over the Atlantic Ocean, as seen from the SeaWiFS satellite.

System cost and implementation schedule. The cost of the system, including associated research, is estimated to be about \$600 million per year (see cost estimate in appendix A), which is comparable to a satellite program such as the U.S. operational polar-orbiting satellite constellation, or the global cost of the five operational geostationary weather satellites. Historically, the United States launched its first polar-orbiting weather satellite within a few years after it became technically feasible, but the operational system required more than a decade of development and implementation. Similarly, operational geostationary weather satellites were pressed into service a little more than a decade after the technology was proven. A target date of approximately the middle of the next decade for an operational global network of stratospheric aircraft and ocean surface buoys would be possible through intense efforts that are similar to those required in the development of the operational satellite systems. The United States has been able to keep both its operational polar-orbiting system and its geostationary systems operating continuously in the decades since initial implementation. This gives confidence in the event that if the United States or a consortium of nations decided to implement an operational global profiling network, they could maintain it through the decades necessary to make it useful for determining climate trends.

OPERATIONS CONCEPT. It is valuable to propose “strawman” observing systems in the early stages of a system design. Typically, the final deployed system will be significantly different, with changes that reduce costs, increase capability, and correct faulty assumptions. In this section a simple design is presented as a starting point, mainly to expose the concepts associated with the global profiling system. Readers are asked not to take the

details of the strawman system too literally, but, rather, to judge the overall feasibility and value of such systems.

Air vehicles. The combination of ever-more-powerful microcomputers, global communications, and advances in aviation design has spawned an array of

UAVs. A few of those that have the potential to play a role in an operational global profiling system are solar aircraft, such as Qinetiq’s Zephyr; smaller aircraft, such as the Aerosonde (Holland et al. 2001); directed superpressure balloons (Girz et al. 2000; Nock et al. 2001); and larger aircraft, such as the Predator and Global Hawk (Aviation Now 2001). It may be that the optimal operational system will be a heterogeneous combination of these systems. For example, a system that deployed dirigibles to remain for months over a geographic location (“station keeping”) is an alternative to the powered UAVs discussed below. To simplify the exposition, the operational concept presented in this paper will consist solely of a particular high-altitude long-endurance UAV, the Global Hawk.

The characteristics of Northrop Grumman’s Global Hawk are presented in Table 1, and a picture is presented in Fig. 5. With a range of 22,000 km

Range	Speed	Peak altitude	Payload	Lease cost
14,000 miles	350 kt	65,000 ft	1960 lbs.	\$4 million per year



FIG. 5. The Northrop Grumman Global Hawk in flight test.

(14,000 miles), it can reach any point on the Earth in a single flight. Recently, a test version was flown nonstop from California to Australia. Its cruising level, from 15 to 19 km (50,000–65,000 ft), is above 14 km (45,000 ft, the ceiling of most commercial aircraft), eliminating many of the concerns about safety. Its location in the stratosphere, above the clouds, would make it valuable for measuring upwelling radiation. The proposed network would allow the UAV to operate exclusively in international airspace, except for landings and takeoffs. The fact that it will have excellent worldwide communications (e.g., using the Iridium system) and an accurate location from an onboard GPS will allow it to be routinely under air traffic control when needed. Its payload of approximately 1000 kg will allow a formidable array of onboard instruments, remote sensors, and deployable sondes. Its flight speed of 350 kt will allow it to cover the grid separation between points (Fig. 1) in 3 h, even in the presence of a strong headwind. In summary, it is a powerful tool that can be used to support atmospheric and oceanic science.

Flight operations. The following is a possible strategy for flight operations. A total fleet of about 36 aircraft deployed at 12 bases worldwide (3 per base) would be needed to cover the 240 points every 3 days. The bases would be geographically distributed over the globe, with one aircraft from each base flying for approximately 24 h each day. At any given time about 12 aircraft would be flying, which is a “duty cycle” of 33%. The aircraft would fly a specific set of points, with small changes in order and allocation based on winds. The observations would be made at a specific time every third day at each location (a multiple of 3 h GMT), with different times of nearby points, allowing for the stratification of the long-term dataset through the diurnal cycle. The flight budget is constrained by the fact that the aircraft must reliably make it to each point at a designated time; thus, the distance between climate points is about 1300 km, while the speed of the aircraft would allow a traverse of 3000 km. The difference allows for adaptive observations to be

made, and for cases when the aircraft will encounter strong headwinds. Once a flight, the aircraft will descend to near the surface, taking in situ observations of chemistry, aerosols, and cloud-droplet spectra. In addition, these same measurements could be taken on ascent and descent to the UAV’s home base.

Sondes. The accuracy and detail of the temperature, wind, and moisture soundings are crucial to the detection and attribution of climate trends, as well as for estimation of model fluxes in the vertical. In this section I discuss “climate” sondes of high absolute accuracy and cost, and later discuss “weather” sondes with lower accuracy and cost. A good example of an existing, commercially available sonde that would be adequate for climate purposes is the Vaisala GPS Dropsonde (Hock and Franklin 1999). The characteristics of this sonde, developed by the National Center for Atmospheric Research (NCAR), are given in Table 2. Its weight (390 g) and dimensions (16 in. height \times 2.75 in. diameter) meet international requirements for aviation safety. Its descent rate of only 12 m s⁻¹ eliminates significant hazards as it hits the surface. The data rate from the sonde allows 5-m vertical resolution, which would allow detailed measurements in the boundary layer, and even into the surface layer (approximately 10 m deep). This sonde is accurate for temperature (0.2°C) and moisture (~2%), both of which are extremely important measurements for climate. The use of multiple humidity transducers allows for accurate measurements of moisture from the lower stratosphere to the surface. This is important because some of the most important signatures for climate change lie in the detailed vertical moisture structure. A goal of the instrument program would be to develop lighter sondes with very high absolute accuracy (e.g., 0.1°C for temperature), estimated to cost about \$1000 per expendable. The high absolute accuracy is important for the detection of long-term climate trends.

Sondes to measure other parameters could also be developed and deployed. Examples include sondes that measure shortwave and longwave radiation, aerosols, and ozone.

TABLE 2. Characteristics for the Vaisala–NCAR dropsonde.

	Operate	Accuracy	Resolution	Time constraint	Typical error
Pressure	1060–20 mb	0.5 mb	0.1 mb	<0.01 s	1.0 mb
Temperature	–90°–45°C	0.2°C	0.1°C	2.5°–3.7°C	0.2°C
Humidity	0%–100%	2.0%	0.1%	0.1–10 s	<5%
Winds	0–150 m s ⁻¹	0.5 m s ⁻¹	0.1 m s ⁻¹		0.5–2.0 m s ⁻¹

In situ instruments. The Global Hawk aircraft, with a payload of approximately 1000 kg, could carry instruments for in situ measurements of trace gases, aerosols, and cloud properties. Suitable instruments fall into two classes. In one class, instruments would be chosen to make routine measurements on all flights based on the simplicity of operation and maintenance, and on meteorological or chemical importance. Candidate measurements are ozone, water vapor, carbon monoxide, carbon dioxide, small aerosol particles (<1 μm diameter), and ice particles. An example of an optical particle probe used on the ER-2 aircraft is shown in Fig. 6. The other set would include instruments for specific episodic research programs, or those that require more preparation prior to flight, and possible maintenance and calibration after each flight. These instruments would be flown in subgroups along with the first class in short intensive flight series. A series would last perhaps several weeks and be repeated a number of times per year as resources allow. The candidate measurements for this class form a larger group as listed in Table 3. In the United States, the National Aeronautics and Space Administration (NASA) ER-2 high-altitude aircraft (<70,000 ft) and the NASA DC-8 medium-altitude aircraft (<40,000 ft) have payloads with many directly suitable instruments or others that could be adapted for autonomous flight (Singh et al. 1999; Newman et al. 1999).

Instruments on aircraft, unlike satellites, can be swapped in or out every day, thus, providing for an ongoing “real-time interactive” research component of the proposed system. For example, if a volcano erupts, sondes could be dropped through the plume (with precautions to protect the aircraft, of course).

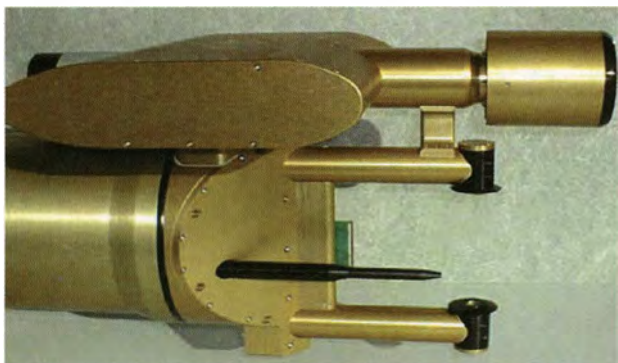


FIG. 6. The Cloud Aerosol Precipitation Spectrometer, designed to measure properties of clouds and aerosols from an aircraft mount. This instrument, manufactured by Droplet Measurement Technologies, can measure a large range of particle sizes from 0.3 μm to 1.55 mm with a single probe.

Of particular importance for climate forcing is the characterization of the detailed cloud and precipitation droplet spectra, condensation nuclei, light scattering, aerosol size spectrum, and aerosol chemistry. Many of these measurements are possible with current techniques. The Indian Ocean Experiment (INDOEX) has shown that anthropogenic aerosols can cover significant portions of an ocean, and that their chemistry is complicated (Ramanathan et al. 2001; Lelieveld et al. 2001). For example, the soot particles seen in INDOEX could be associated with warming, while more effective condensation nuclei would result in cooling because of increases in cloud cover. Recently, in situ instruments have been developed that can determine soot content in aerosols with the aid of a powerful laser pulse.

The proposed system would enable the sophisticated long-term chemical monitoring of the atmosphere. Currently, the National Oceanic and Atmospheric Administration’s (NOAA’s) Climate Monitoring and Diagnostic Laboratory maintains a network of stations, and routinely collects “flask” samples of the atmosphere at many surface locations. The aircraft could be equipped to routinely collect air samples at many levels at each of the profiling points on descent, which could be returned for sophisticated chemical analysis. One important application of such analysis is to determine carbon isotope ratios; along with air trajectories, these could help explain the carbon cycle, especially the sources and sinks of carbon dioxide.

Remote sensors. Almost all of the remote sensors developed for the satellites could (depending on

TABLE 3. Possible in situ instruments for the Global Hawk payload	
Instrument class	Autonomous instruments
1: Routine flights	Ozone, water vapor, carbon-monoxide, carbon dioxide
	Small particles (condensation nuclei), ice particles
2: Intensive flight series	Nitrogen oxides, sulfur oxides, organic nitrates, hydrogen peroxide, hydroxyl radicals, halogen oxides, peroxy radicals, hydrocarbons, formaldehyde, long-lived halogen species, nitrous oxide, methane, sulfur hexafluoride
	Soot particles, ice nuclei, liquid cloud droplets, cloud water, aerosol chemical composition

weight, size, expense, etc.) be used on the aircraft platform, including microwave radiometers, lidars, infrared spectrometers, scatterometers, and radars of many types. Radiometric and lidar instruments have been used successfully on the ER-2 aircraft to study the atmosphere (e.g., Smith et al. 1998; Wang et al. 1998). An in-depth systems analysis would be required to determine which remote sensors should be located in each of the three “remote” tiers (geostationary, polar orbiting, or stratospheric) in order to optimize the information needed for weather and climate models. As one example, lidars are valuable for characterizing profiles of winds, water vapor, aerosol/cloud properties, and chemical constituents, such as ozone. Currently projected space-based lidars for measuring winds, water vapor, or ozone will be hampered by relatively weak signals, necessitating the spatial averaging of as much as several tens or even hundreds of kilometers. Because the signal from a lidar observing the troposphere from a Global Hawk will be about 25 dBZ stronger than that from an equivalent instrument deployed on a satellite, a combination of better horizontal or vertical resolution or improved measurement precision is obtainable from the aircraft platform. Flying a lidar in the lower-stratosphere rather than Earth orbit would also be very advantageous for tropospheric ozone observations, because a portion of the strong ozone concentrations in the stratosphere that obscure the lower-tropospheric ozone can be avoided. Of course, the cost of an individual lidar used in the aircraft fleet must be multiplied by the number of aircraft to compare its cost with the satellite system.

A new generation of moored buoys. It is proposed that each profile point of the observing system in the ocean would include a buoy. Modern technology, including computers, materials, batteries, and communications, has broadened the capabilities of buoy platforms, while decreasing their cost. The ocean observing system would be based on a new generation of moorings based on the TAO buoys. They were referred to as the “crowning achievement of TOGA [Tropical Ocean Global Atmosphere]” field experiment (McPhaden et al. 1998) because they led to a much greater understanding of El Niño–Southern Oscillation (ENSO). The existing TAO buoys provide real-time measurements of key oceanographic variables: surface winds, sea surface temperature, subsurface temperature and salinity, and sea level and current. The new mooring (Fig. 7), called Platform and Instrumentation for Continuous Ocean Observa-



FIG. 7. Two views of the PICO buoy: (a) being readied for deployment, and (b) as deployed. It is designed to be easy to deploy, inexpensive, and require significantly less on-site routine maintenance than the TAO buoys.

tions (PICO), is under development by Pacific Marine Environmental Laboratory (C. Meinig 2003, personal communication). These buoys have numerous advantages over the TAO series, including low initial cost, small size, safer operations, self-deployment from ships or aircraft, and vandal resistance. They automatically unspool a cable that can go to the bottom of the ocean, as deep as 4000 m. This taut line can be used for “crawlers,” which are instruments

that move up and down to take acoustic, chemical, or biological measurements. This buoy would be very cost effective because of its low deployment cost and low maintenance, resulting from a goal of site visits once every 3 years rather than the twice-a-year frequency that is needed by TAO buoys. The proposed network would require about 200 PICO buoys in its operational configuration.

The scientific value of a global set of fixed buoys will be substantial. They could be used to calibrate other observations, such as floating buoys and ship observations. Experience with the TAO array in the equatorial Pacific showed that the all-important coupling between the atmosphere and the dynamics of the subsurface layer was crucial to understanding the atmosphere–ocean interaction. The temperature of the ocean’s surface varies on small scales (on the order of 100 km), which means that estimates of interactions between the ocean and atmosphere require that profiles of atmospheric conditions be nearly collocated with the ocean measurements.

The ocean community has worked to establish “a consensus on the most viable candidate technologies and implementation strategies for implementing a comprehensive, integrated, international observing system in support of ocean research, forecasting and climate assessment” (Smith and Koblinsky 1999). The proposed network should be considered as a part of the full system that is needed to meet these goals. They emphasize that a full understanding of the ocean will require the complementary aspects of widespread subsurface measurements [e.g., *Argo* floats and the volunteer observing ship (VOS) program] and the worldwide remote view of the ocean from satellites (e.g., sea surface temperatures and space-based ocean altimetry), together with the detailed ocean–atmosphere coupling that the global buoy program can supply.

CLIMATE MONITORING AND PREDICTION.

Seasonal to interannual climate prediction. The combined observing system should lead to a significant improvement in seasonal to interannual climate prediction. The extension of moored buoys in the open ocean outside of the Tropics would allow extratropical structures, such as the Pacific Decadal Oscillation, to be better characterized. When the natural oscillations of the upper ocean, such as the Pacific Decadal Oscillation (plus others that may be discovered using the new oceanic observing systems), are better understood, the next step will be to develop more realistic coupled ocean–atmospheric models. The prediction of the large El Niño of the late 1990s showed the eco-

nomie value of seasonal to interannual prediction—a factor of no small importance when measured against the cost of the proposed system.

Inadequacy of current upper-air network. The primary justification for the global profiling systems presented in this paper is the importance of detecting, attributing, and predicting long-term (decadal to centennial time scales) global change. The difficulties associated with the use of the current global upper-air network for climate have been discussed in NAS (1999). There are efforts by the Global Climate Observing System to maintain and improve the upper-air network (WMO 1998), but the global network is deteriorating rather than improving. The total number of radiosondes has declined since 1990, particularly in the former Soviet Union, Africa, and South America. Few tropical stations report reliably. Hurrell and Trenberth (1998) point out that the radiosonde record is made up of differing instruments, with nonoverlapping changes to instruments over time, discontinuous records, and a lack of sufficient metadata. Most important, the proposed observing system will increase the area of the Earth with representative detailed vertical sampling from about 15% to nearly 80%. This network would replace the twentieth-century network, which is poorly distributed globally, inconsistent in time and data quality, and unreliable for the future, with a twenty-first-century system. It would be superior in every respect when judged by the climate monitoring principles laid out by the NAS (1999).

Network spatial and temporal requirements for climate monitoring. In this section I describe the various considerations that are used to determine the spatial and temporal scales required of a climate monitoring system profiling atmospheric state variables. These studies were led by Elizabeth C. Weatherhead, based on her expertise in climate trend detection (Weatherhead et al. 2002, 1998).

An important question concerns the horizontal scale of soundings dictated by the integrated use of satellite and in situ profiles. Figure 8 presents a 20-yr time-averaged horizontal correlation of channel 4 of the U.S. operational polar-orbiter Microwave Sounding Unit between a point over San Francisco, California, and the rest of the globe. The horizontal scale of variation is seen to be a few thousand kilometers, associated with midlatitude, lower-stratospheric synoptic waves. This implies that if a detailed vertical sounding is available, its temperature structure can be used in an analysis system to relate it to temperatures over similar length scales. The implied length scale

MSU Channel 4 Correlation with S.F.

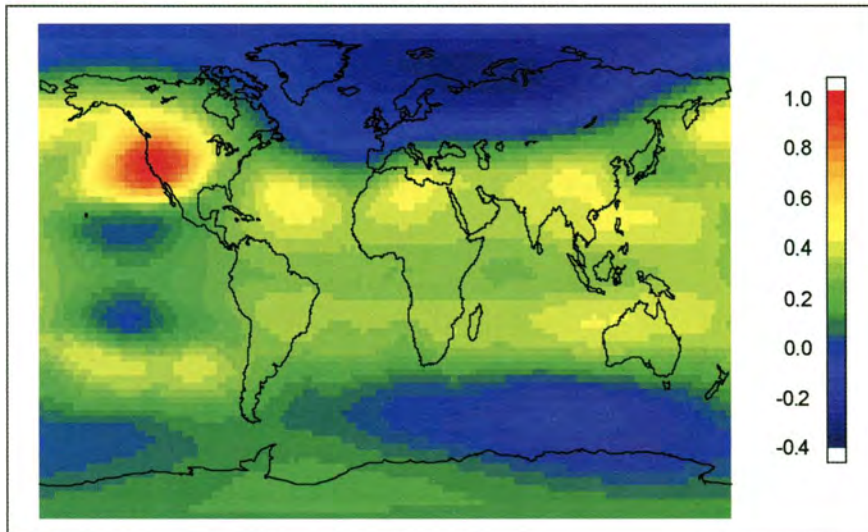


Fig. 8. Correlation of channel 4 of the U.S. polar orbiter **Microwave Sounding Unit (MSU)** with microwave signal from a point over **San Francisco, CA**. The correlation coefficient ranges from **+1** (perfect correlation) to **-1** (perfect anticorrelation), as color coded in the scale on the right.

for in situ profiling for use with satellites is, thus, a few thousand kilometers.

An independent measure of the appropriate length scale for climate state profiles comes from studies done by E. C. Weatherhead (2003, personal communication). In order to determine this, she used the 40-yr radiosonde database developed by the Forecast Systems Laboratory (Schwartz and Govett 1992). Significant efforts were put into assuring the quality of these soundings. Detailed (every 10 mb) profiles of temperature change for nine stations from three different geographic areas over 40 yr are shown in Fig. 9. The data were deseasonalized and subjected to a linear least-squares fit. All nine of the stations have used the same type of radiosondes, which have changed several times during the 40-yr period. The top row is from Alaska, the middle row is from the Mountain West, and the bottom three stations are from the eastern United States. The stations in each geographic area have surprising agreement of their temperature trends, extending to details in the vertical. Yet each of the three geographic areas shows substantially different trends when compared with the other two geographic domains. This shows that the vertical details of temperature change are significantly different over scales of a few thousand kilometers (e.g., between the eastern and western United States). The network discussed in this paper has horizontal spacing of 1300 km, so it would typically resolve the major climate change differences seen over these geographic scales.

A third consideration for the spatial scale of the climate soundings is a practical one. Almost all of the costs of obtaining climate soundings in the proposed network are associated with the operation of the UAVs; a much smaller portion is due to the cost of the expendable climate sondes themselves. Thus, if a lower-density (e.g., only 60 stations) network were used, the cost of the whole system would be almost as much as the 240-station network. As long as the UAVs are trying to cover the whole international airspace over oceans and polar regions, dropping more sondes does not add much to the cost. Fortunately, the

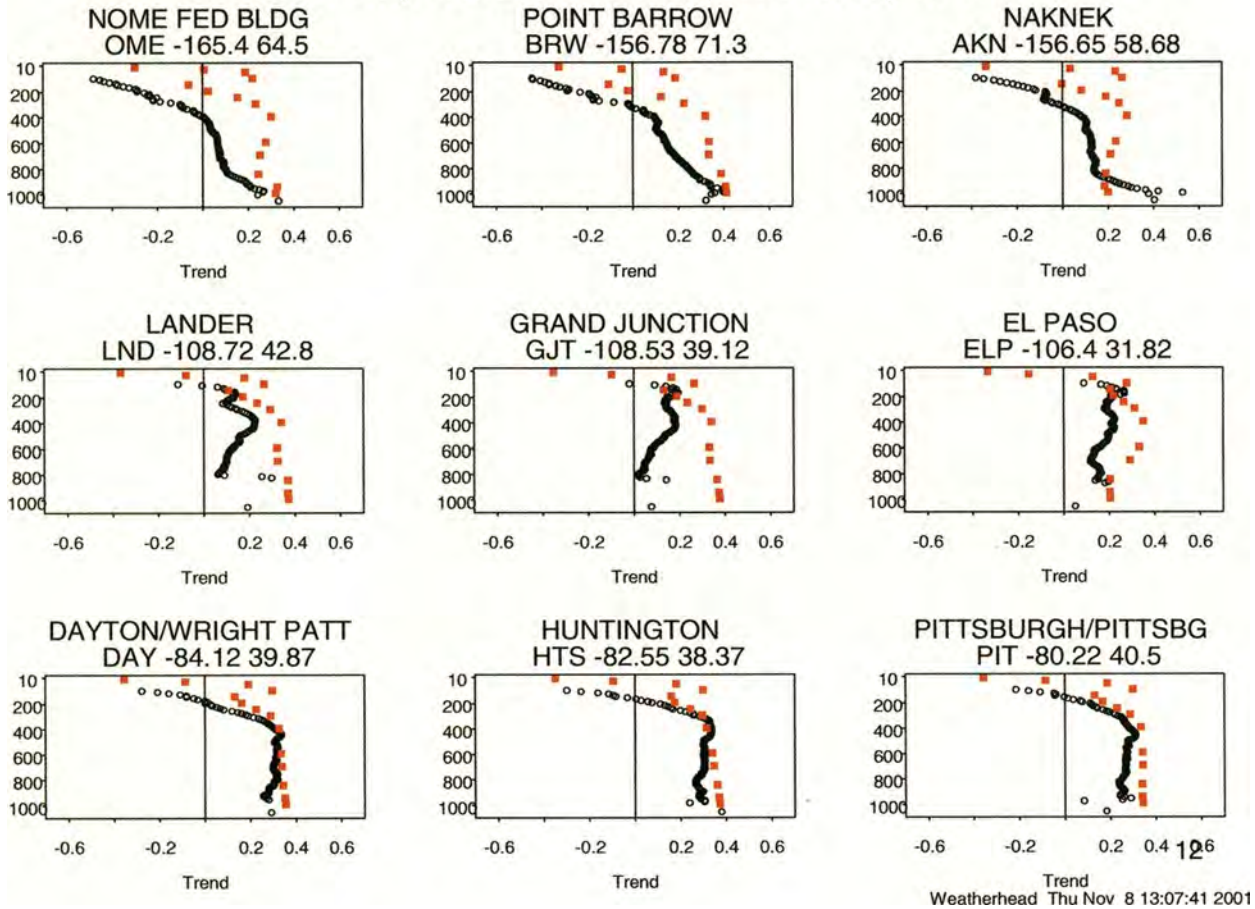
proposed network density satisfies all three scaling considerations.

The optimum temporal frequency of the climate soundings was determined in another study by E. C. Weatherhead (2004, personal communication). A graph of the climate trends for 500-mb temperature from the Dulles, Virginia, radiosonde over the last 40 yr is shown in Fig. 10. The data for days of the month are systematically removed to determine how often soundings are needed to establish stable long-term trends. The trend using all of the data is shown as a horizontal solid line. As seen in the figure, the trends are very accurate, with sondes taken every 3 days (10 per month); but for those taken less often, the climate trends become less accurate. The choice of one climate sonde every 3 days was based on this study.

Role of the proposed system in diagnosing climate change feedbacks. The most important issue associated with long-term anthropogenic-forced climate change is feedback. As shown in Fig. 11, the most important feedbacks include changes in upper-atmospheric water vapor, changes in low cloudiness, and the depth to which warming will occur in the ocean. The network of the global, spatially unbiased, highly accurate profiles that is proposed in this paper would be very valuable in diagnosing these feedbacks.

Changes in water vapor are probably the most crucial long-term climate feedback, but such changes

Sonde Temperature Trends (C/decade) at 12 Z

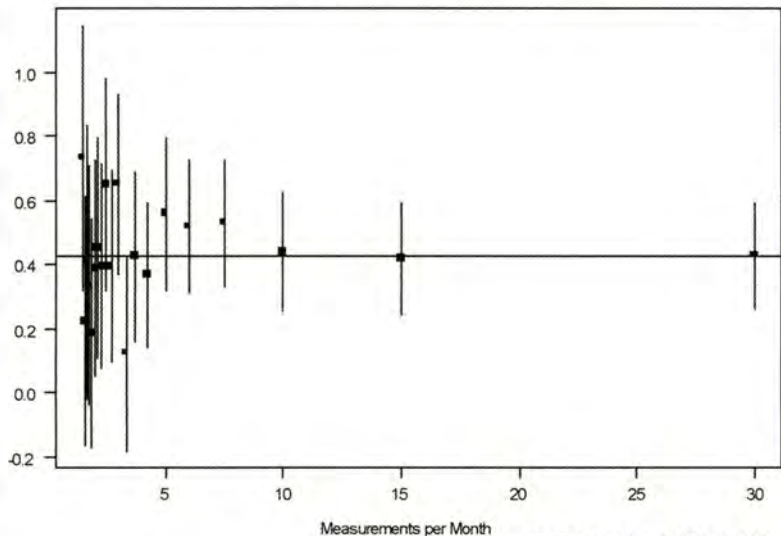


Weatherhead Thu Nov 8 13:07:41 2001

FIG. 9. Forty-year (1956–96) trends of 1200 UTC radiosonde temperatures (black dots) for three stations in each of three different regions (Alaska, Mountain West, and eastern United States) of North America. The trends show a surprising similarity to others in their region, but are different in the three regions. This study helped establish the horizontal density needed for the global profiling system. The Hadley Centre CM3 model change for the same period is shown in orange.

500-mb Temperature Trend, Dulles

FIG. 10. Temperature trend at 500 mb over Washington Dulles International Airport determined from 40 yr of radiosonde data. The data were selectively withdrawn, where 30 per month corresponds to one sounding per day, and 15 corresponds to one sounding every 2 days. The horizontal line represents the trend determined from two soundings per day, the square symbol represents the mean trend, and the vertical lines represent the trends within one standard deviation. One sounding every 3 days (10 per month) accurately represented the long-term temperature trend.



Weatherhead Wed Jun 5 12:52:10 2002

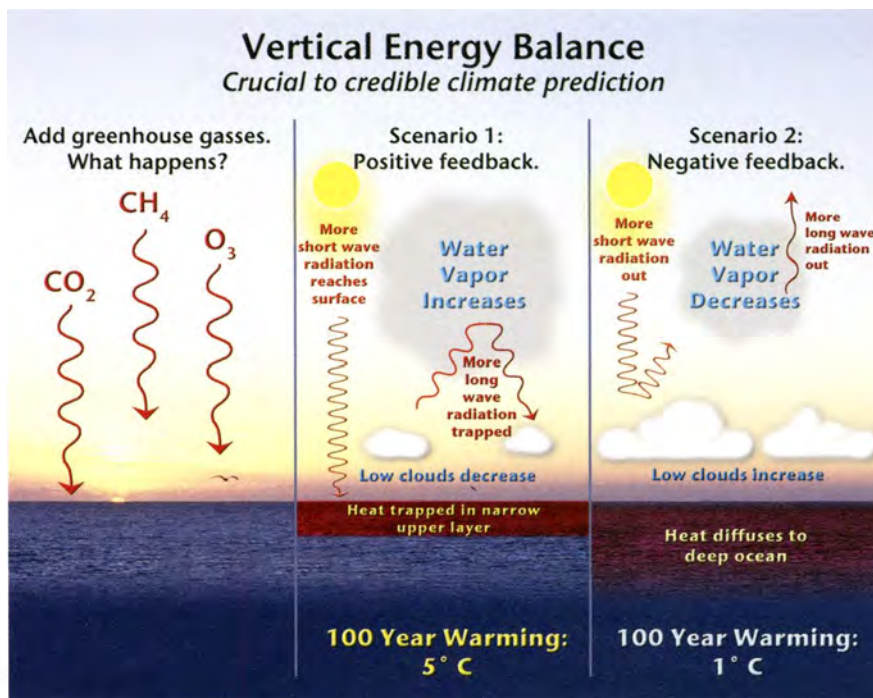


FIG. 11. The feedback of the atmosphere–ocean system to the addition of greenhouse gasses results from adjustments in the vertical energy balance. Credible climate prediction will require globally comprehensive measurements of vertical profiles of state and forcing.

are very poorly known in the current global observing system. Satellites give a broad picture, but are poorly suited to determine precise water vapor trends as a function of height through the decades. The only extended time series of water vapor with a high absolute accuracy from sondes has been made by Oltmans et al. (2000), who used a chilled mirror to get upper-tropospheric and lower-stratospheric humidity near Boulder, Colorado, for the last 15 yr. (Recently, a second location has been instituted in New Zealand to take similar measurements.) The proposed network would increase the number of sites where long-term, very accurate water vapor profiles are available in the upper atmosphere from 2 to 240 over the globe, and if the proposed land network is included, to approximately 360. As discussed by Held and Soden (2000), the change in upper-atmospheric water vapor in the model predictions is crucial to the climate sensitivity (i.e., the amount of equilibrium global warming that would result from a doubling of carbon dioxide). The network proposed in this paper would be particularly valuable in determining the water vapor feedback in the early decades of this century, allowing for better estimates of climate sensitivity.

Atmospheric temperature soundings with high absolute accuracy can be valuable for the vertically

detailed “fingerprint” of climate change that they reveal. For example, in Fig. 9, it can be seen that tropospheric warming differs significantly among the three North American regions shown. In Alaska, the lower troposphere is warming strongly, while the upper troposphere is not. In the western United States the opposite is evident in the vertical trends—the lower troposphere has barely warmed, while the upper troposphere has strong warming. In the eastern United States, there is a different pattern again—equivalent warming in both the lower and upper troposphere. In general, the climate models (e.g., the Hadley Centre CM3, whose temperature change is shown in orange

in Fig. 9) did not capture these fingerprints of vertical warming. Because these changes in the temperature are due to important physical causes (e.g., global-scale wave structures or changes in regional forcing), accurate temperature trends over the globe would serve as an important constraint on climate models (Palmer 2001). Those models whose vertical changes in temperature and moisture correspond to the observed changes would inspire added confidence in their predictions of global and, most important, long-term regional climate change.

Two other examples of the value of the proposed network relate to the changes occurring over the Arctic Ocean and the vertical distribution of the warming in the ocean. The use of sondes dropped from the stratosphere is an ideal way to detect climate change at fixed points over the Arctic Ocean, which currently, despite its importance, has no routine radiosondes. Balloon radiosondes that are released from the ice (e.g., from ships or from ice stations) typically move with time as the ice moves. The UAVs could drop sondes at the same geographic points through the decades, determining the crucial trends in temperature and wind in the shallow layers right above the Arctic Ocean. A goal of the program would be to develop buoys that could maintain position under ocean ice.

Barnett et al. (2001) have discussed the importance of detecting the trend of ocean heat content in understanding and predicting long-term climate change. In the global ocean, the PICO buoys would be able to measure very accurate trends of temperature and salinity to determine how deep the “greenhouse”-forced heating penetrates into the ocean.

Universality and realism in numerical prediction models.

Numerical weather and climate prediction models always require approximations (parameterizations) of the physical laws that govern their geophysical constituents (atmosphere, oceans, etc.). The history of numerical prediction during the last 50 yr has been to increase spatial detail, and to increasingly refine parameterization of the physical processes, such as radiation, cloud microphysics, and turbulence. In this paper, the process of replacing a cruder parameterization (e.g., all longwave radiation treated as a single band) with a more sophisticated version (e.g., longwave radiation treated separately in many frequency bands) and increasing resolution will be referred to as increasing model *universality*. It is based on the premise that a model more closely approximating the true physical processes should be more universally applicable than a highly empirical model (Palmer 2001). The drive toward more universal models has been aided by the ongoing decrease in the cost of computation—a trend that is likely to continue for many decades. Although a more universal model will not necessarily result in a better prediction, the impetus for increasing universality is that the finer the spatial scales and the more complete the physical parameterization, the more generally applicable and accurate their models become. This has certainly been the experience of modelers. “*Realism*” refers to the degree to which a model prediction corresponds to observations extended over time and space. It is distinct from universality in that realism relates to the correspondence of model output to observations, while universality concerns the formulation of physical laws in the model code. I suggest that the best way to improve climate models in the coming decades will be to increase their sophistication and resolution (universality), while continually testing their correspondence to globally comprehensive observations (realism).

Two examples illustrate how the concepts of universality and realism enter the modeling process. During the last 10 years I helped develop a new mesoscale weather prediction model (MacDonald et al. 2000a,b). When a very limited space and time domain was used, say Colorado in March, the model

could accurately predict the surface temperature, despite a simple empirical model of the soil and a low-resolution (five layer) boundary layer. When the domain was enlarged to extend from the California coast to the Midwest, the simple scheme “tuned” to Colorado failed, producing temperatures in Oklahoma of 50°C in May. With more sophisticated soil and vegetation (Smirnova et al. 1997) and a 31-layer boundary layer (Zhang and Anthes 1982), the model was able to predict reasonable temperatures over differing geography and throughout the year. The former model, despite empirical adjustment, could not properly exchange heat, moisture, and momentum between the ground, surface layer (0–10 m) and boundary layer (1–2 km deep). This is one of numerous examples where realism of the model (i.e., its correspondence with observations) was enhanced by increasing the model’s universality.

The example above relates to the correspondence of model fields to observations as they vary over geography. A similar concept can be illustrated for the vertical column. Many models overforecast tropospheric cloudiness (Somerville 2000; Iacobellis and Somerville 2000). If one is only interested in surface temperature, the radiation calculations (both shortwave and longwave) and the surface characteristics (e.g., the albedo and heat capacity of the soil) can be adjusted to give the correct temperature. In doing so, however, the modeler necessarily must generate false irradiative flux divergence in the atmosphere, or perhaps radiate an excess of energy from the top of the atmosphere. If, instead of tuning the model for surface temperatures, the modeler is also trying to predict accurate profiles of temperature, irradiative flux divergence, and radiation outgoing to space, the model must be made more universal. When the water vapor and temperature profiles are correct, the amount of cloud seen in the model corresponds to the amount of cloud seen from satellites, and when the depth and irradiative properties (e.g., as determined by droplet size distribution) of the clouds and aerosols correspond to those of measured profiles, the modeler has adequate information to develop a model that is correct through the whole column. By increasing the universality of the model, the realism of the vertical column is increased.

The logical extension of this concept is clear—we should require our models to deliver diagnostically correct fields of state variables, fluxes, and other forcing over the entirety of the Earth’s atmosphere, oceans, land, and ice. The more universal and realistic climate models are today for short predictions, such as seasonal to interannual projections, the more credible and accurate they should be for long-range forecasts.

WEATHER PREDICTION. UAVs could be very useful for continuous tracking of tropical cyclones from genesis through landfall. Cruising in the stratosphere above the cloud tops, they could drop sondes and use remote sensing to continuously monitor the ocean surface, eyewall, and inner portion of the storms. They would be complementary to manned hurricane reconnaissance, which covers larger domains, but not continuously. In the wake of the disaster caused by Hurricane Katrina, the ability to monitor storm intensity and structure for long periods from UAVs could be important for advancing understanding and prediction of these destructive storms.

The proposed system would have, in addition to the “climate” sondes, two types of sondes to help improve medium-range (1–14 days) weather forecasts. One type would be a dropsonde designed to be as inexpensive as possible, while maintaining the accuracy that is needed for weather (instead of the extremely high absolute accuracy that is needed for climate trends). The other type of sonde, referred to as a “sidesonde,” would be a small superpressure balloon that would be released from the UAV, fall to a level (e.g., between 5 and 6 km), and float along at that level reporting winds and temperature for a period averaging a few days. In addition, onboard remote sensors such as lidars, microwave radiometers, and infrared interferometers could be used for weather observing. In this section I describe the design and proposed use of the sondes, and close with the test program that is needed to determine the optimal use of the UAVs for improvement of weather prediction.

Adaptive observing. A number of experiments in recent years have established that weather predictions can be improved by adaptive sounding—choosing the best time and place to take observations based on the atmospheric state (e.g., Toth et al. 2001; Szunyogh et al. 1999, 2000; Abernethy and Franklin 1999). The flight budget for the operations concept described in this paper would allow unstable areas (e.g., baroclinic or barotropic instabilities that result in rapid change of atmospheric waves) to be sampled extensively. Similarly, it is possible to use weather models (more specifically, the adjoint of a weather model) to determine the areas where more comprehensive observations can have a significant effect on initial conditions and a subsequent forecast of high-impact weather (e.g., a deep low pressure system that will affect populated areas a few days in the future). The operations concept of the proposed system would foster improvements in the initial state of critical regions.

Weather dropsondes. The “weather” dropsonde should be inexpensive, so that large numbers can be deployed, small and light, and either biodegradable or denser than water so that it sinks to the bottom of the ocean. The design goals for this sonde include a cost below \$50 per sonde and a weight of no more than 50 g. To achieve this, the sonde will communicate with the UAV, which requires that it drop fairly rapidly from flight level to the surface, in order to keep the aircraft in radio range. Nominally, the weather sondes could be dropped every half-hour at an average spacing of every 300 km for a UAV traveling at 600 km h⁻¹. Adaptive observing using the weather dropsondes would involve determining sensitive areas, and using the available flight budget to direct the aircraft to these areas, where they could drop a relatively large number of the sondes.

Weather sidesondes. The sidesondes are a new concept that will require significant development to prove viability. The idea is to have a light, frangible canister that is not dangerous to aviation, and is similar in size to, but half the diameter of, a 12-oz aluminum soft drink can. The canister would be made of plastic and dropped from the UAV. A pressurized chamber would fill a small balloon with a lifting gas, allowing the balloon to float when it reaches a designated buoyancy level. They would be designed so that each one would drop to a particular level, with many different levels of the atmosphere possible (e.g., every hundred millibars from 200 to 900 mb). With a design goal of lasting several days (before icing or other problems bring them down), the sidesondes would radio their location (based on GPS) and temperature to commercially available low-Earth-orbit satellites (e.g., the Iridium system). The location of the sidesonde releases would be determined by weather models so as to provide optimal trajectories through forecast-sensitive areas over the subsequent several days. A reasonable set of assumptions for the sidesondes indicates a potential for 50,000 observations per day of wind and temperature in these key weather-sensitive areas.

Test program for weather systems. The idea of both routinely and adaptively taking measurements of state variables from sondes and remote sensors, biased strongly to weather-sensitive areas, has significant potential, but will require extensive development and testing. Two aspects of The Hemispheric Observing System Research and Predictability Experiment (THORPEX) (Shapiro and Thorpe 2004) will be useful in this regard. The first is to join in some of the planned tests, such as those proposed for the Pacific

and Atlantic Oceans, to determine if the adaptive observations of the type described above have a significant effect on weather forecasts. A second effort would be to run an extensive set of observing system simulation experiments (OSSEs) to see if the proposed global operations concept would affect weather predictions, particularly high-impact predictions such as the track and intensity of tropical storms and dangerous midlatitude storms.

The proposed development period of at least a decade will allow concepts for improving weather predictions to be tested and evaluated. If they prove out, the system could be instrumental in improving medium-range weather predictions. If they do not, the justification for the proposed network is weakened.

Ocean weather prediction improvements. The skill of weather prediction for small-scale severe events over oceans is significantly less than that of continents where radiosonde density is adequate. A study of analyses differences between the National Centers for Environmental Prediction (NCEP) and European Centre for Medium-Range Weather Forecasts (ECMWF) by Nutter et al. (1998) differed substantially in the oceans and polar regions. The addition of both fixed and adaptive soundings over the oceans should improve model initial states in these regions and result in significant improvements of oceanic weather prediction skill. The marine community, which is vulnerable to storms on the high seas, would be a major beneficiary of the improved oceanic predictions.

CONCLUSIONS. *Design, development, and implementation.* A global observing system to improve weather and climate prediction by taking long-term detailed profiles of the oceans and atmosphere has been described. This system must involve the international community from the beginning. A number of international programs must be engaged, such as the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Climate Variability and Prediction Program (CLIVAR); these are sponsored by the World Meteorological Organization, the Intergovernmental Oceanographic Commission, and the United Nations Environmental Program, respectively. The joint project for *Argo* is a good example of how such an international effort can be organized.

The system discussed in this paper would require that an intense effort be implemented by the middle of the next decade. As with many systems, early develop-

ment is less expensive than full deployment and can answer many questions about feasibility. A project to test a couple of aircraft and a limited set of buoys could be in place to participate in THORPEX, which is now scheduled for later in the decade. The aircraft, based out of Hawaii and Alaska could be tested over the North Pacific and the Arctic.

Importance. Long-term climate change forced by greenhouse gases may well become the most important issue of the twenty-first century. In addition to long-term change, there is a danger of abrupt regional climate change (MacDonald 2001). The economic prosperity of nations is now tightly coupled with the burning of fossil fuels and the associated release of carbon-carrying molecules into the atmosphere. The main tool that policymakers have in judging the need to reduce fossil fuel consumption will reside in the credibility and reduced uncertainty of long-range climate predictions.

The proposed system is an essential part of the required global observing system. Its cost, estimated at about \$600 million per year, as shown in appendix A, would increase the global expenditure on weather and climate observing systems (estimated at about \$8 billion by R. Hallgren 2001, personal communication) by less than 10%.

What will be the factor limiting improvement of climate predictions as the century wears on? We can expect computers to get faster and our understanding of the physics of Earth's encircling spheres to improve with time. *Probably the most important resource, one that cannot be recovered no matter how great the need and desire later in the century, is comprehensive, accurate, and consistent measurements of the global atmosphere and ocean.* We enter the twenty-first century with a patchwork system—one that has deteriorating observations over the continents, and a large portion of the Earth with very poor measurements of the basic state of the ocean and atmosphere. Furthermore, as feedback effects and anthropogenic chemicals and aerosols increasingly dominate the planet, we will lack detailed and accurate measurements of these important climate-forcing agents *as they change with time.* In almost every case, satellites can provide part of the answer, but the full answers can only be achieved by a composite system—all four tiers. Every year that passes without the proposed system in place is a year that will withhold many of its mysteries from the scientists of the future.

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APPENDIX A: ESTIMATED COST OF THE PROPOSED SYSTEM. The costs of the described system cannot be estimated accurately because of a number of factors. The UAVs that are currently used by the military are specifically tailored to the military mission, and could be modified to be significantly less expensive to meet the mission described in this paper. Nevertheless, it is important to estimate the costs, even if crudely, as follows:

Lease of 36 aircraft, estimated at \$4 million per aircraft per year:	\$144 million
Lease of 12 bases, estimated at \$3 million per year:	\$36 million
Operating personnel (estimated at \$100 thousand per person per year):	
bases, 15 people per base for take-off and landing support:	\$18 million
center, 15 people per base (3 per aircraft in flight):	\$18 million
Operating costs of UAV (fuel, maintenance, etc.), estimated from contractor figures at \$2000 per hour:	\$210 million
Communications:	\$50 million
Climate sondes, assuming \$1000 per sonde:	\$29 million
Weather dropsondes (48 per flight at \$50 each):	\$11 million
Weather sidesondes (50 per flight at \$50 each):	\$11 million
PICO buoys (200 buoys, lease cost \$50 thousand per year):	\$10 million
PICO buoy maintenance (\$50 thousand per buoy per year):	\$10 million
PICO buoy operations:	\$8 million
Data management:	\$20 million
Instrument development:	\$30 million
Monitoring research:	\$25 million
Total cost per year:	\$630 million

APPENDIX B: WORKSHOPS ON THE ROLE OF UAVS GEOPHYSICAL MONITORING.

Two workshops have been held to discuss the role of UAVs in geophysical monitoring, and a third was held to discuss the upper-air observing systems that are needed to monitor long-term climate:

Workshop 1: This was hosted by the Scripps Institute of Oceanography on 3 and 4 August 2004. The purpose of the workshop was to determine the potential role that UAVs could play for atmospheric weather and climate prediction. The workshop is summarized online at http://uav.noaa.gov/uav_workshop/uav_workshop1/index.html.

Workshop 2: This was hosted by an interagency group consisting of NASA, NOAA, and Department of Energy (DOE) representatives, and was held in Boulder, Colorado, on 7 and 8 December 2004. Its purpose was to determine the available UAV technology for geophysical monitoring. The workshop is summarized online at http://uav.noaa.gov/uav_workshop/uav_workshop2/.

Workshop 3: This was led by NOAA and the WMO. It was hosted in Boulder, Colorado, by NOAA's Forecast Systems Laboratory and the Cooperative Institute for Research in Atmospheric Sciences (CIRES) of the University of Colorado on 8–10 February 2005. The results of the workshop are summarized online at www.oco.noaa.gov/index.jsp.

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