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Toward Robust Climate Baselining: Objective Assessment of Climate Change Using Widely Distributed Miniaturized Sensors for Accurate World-Wide Geophysical Measurements

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TOWARD ROBUST CLIMATE BASELINING:

Objective Assessment of Climate Change Using Widely Distributed Miniaturized Sensors For Accurate World-Wide Geophysical Measurements*

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ABSTRACT

A gap-free, world-wide, ocean-, atmosphere-, and land surface-spanning geophysical data-set of three decades time-duration containing the full set of geophysical parameters characterizing global weather is the scientific perquisite for defining the climate; the generally-accepted definition in the meteorological community is that climate is the 30-year running-average of weather. Until such a tridecadal climate baseline exists, climate change discussions inevitably will have a semi-speculative, vs. a purely scientific, character, as the baseline against which changes are referenced will be at least somewhat uncertain.

The contemporary technology base provides ways-and-means for commencing the development of such a meteorological measurement-intensive climate baseline, moreover with a program budget far less than the ~$2.5 B/year which the U.S. currently spends on "global change" studies. In particular, the recent advent of satellite-based global telephony enables real-time control of, and data-return from, instrument packages of very modest scale, and Silicon Revolution-based sensor, data-processing and -storage advances permit 'intelligent' data-gathering payloads to be created with 10 gram-scale mass budgets.

A geophysical measurement system implemented in such modern technology is a populous constellation oj long-lived, highly-miniaturized robotic weather stations deployed throughout the weather-generating portions of the Earth's atmosphere, throughout its oceans and across its land surfaces. Leveraging the technological advances of the '90s, the fully-developed atmospheric weather station of this system has a projected weight of the order of 1 ounce, and contains a satellite telephone, a GPS receiver, a full set of atmospheric sensing instruments and a control computer – and has an operational life of the order of 1 year and a mass-production cost of the order of $20. Such stations are effectively "intra-atmospheric satellites" but likely have serial-production unit costs only about twenty-billionths that of a contemporary NASA global change satellite, whose entirely-remote sensing capabilities they complement with entirely-local sensing. It's thus feasible to deploy millions of them, and thereby to intensively monitor all aspects of the Earth's weather. Analogs of these atmospheric weather stations will be employed to provide comparable-quality reporting of oceanic and land-surface geophysical parameters affecting weather.

This definitive climate baselining system could be in initial-prototype operation on a one-year time-scale, and in intermediate-scale, proof-of-principle operation within three years, at a total cost of ~$95 M. Steady-state operating costs are estimated to be ~$75 M/year, or ~3% of the current U.S. "global change" program-cost. Its data-return would be of great value very quickly as simply the best weather information, and within a few years as the definitive climatic variability-reporting system. It would become the generator of a definitive climate baseline at a total present-value cost of ~$0.9 B.

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Introduction and Summary. Climate is generally defined in the meteorological community as the 30-year time-average of then-prevailing weather. Thus, objective scientific detection of climate change necessarily involves quantitative assessment of the state of all climate-impacting aspects of the biosphere, including the atmosphere, the oceans and the land-surface of the Earth for a time-interval of no less than three decades. While satellite-based measurements of some climate-determining parameters over substantial portions of the Earth have been underway for a third-century, adequately quantitative assessment of the full set of geophysical parameters necessary to characterize adequately the Earth's climate – e.g., including the vertical structure of winds and the thermal structure and first-order thermal variability of the deep ocean – has yet to get underway. Furthermore, even partial sets of the pertinent geophysical parameters are measured presently with adequate frequency only where human activities are relatively intensive, i.e., over less than 20% of the Earth's surface, and seldom in either space or time have the full set of weather-defining parameters been measured adequately in terms of precision and absolute accuracy, as well as measurement of associated and potentially confounding variables.

Time-averaging for climate-baselining purposes may obviate some, but not all, of the corresponding deficiencies in contemporary geophysical data-sets, e.g., it can't fill in the geographical 'holes' in meteorological data-sets over the Southern Ocean or Central Asia, let alone the geophysical ones throughout most of the deep ocean. It's therefore difficult, even today, to speak of <u>any</u> future date-certain when the Earth's climate will be baselined even semi-quantitatively, let alone to contemporary scientific standards. Presently-available approximations to a climate baseline are so noise-intensive and so rich in currently-unquantified atmospheric and oceanic natural variability as to impeach the basic scientific qualities of objective, statistically-quantifiable discussions of global climate change.

Quite notably in these respects, integrations of modern sensing, data-processing and -storage and telecommunications capabilities presently offer the prospect of commencing the collection of sufficiently high-accuracy data-sets of sufficiently great spatio-temporal completeness that baselining of the climate of the entire Earth can get seriously underway. As recently as a decade ago, only the U.S. Defense Department could deploy and operate such a system, one reaching from ocean bottom to the mid-stratosphere, uniformly and densely, all over the planet. Today, due to the enormous technological advances of the '90s, doing so is well within the reach of less well-endowed organizations, e.g., the U.S. Department of Energy.

Creation and operation of such a system will not only serve to baseline the climate up to standards of modern science, but will provide the earliest possible *objective* indication that the Earth's climate isn't time-stationary within accepted statistical norms, i.e., that large-scale climate-change is actually underway. Intelligently performed, the cost of creating and operating such a system over a climate baselining interval will be a fraction of a single year's cost of ongoing "global change" studies in the U.S. Its collateral benefits, e.g., with respect to greatly enhanced weather prediction, can be expected to be remarkably large.

Technical Approach Essentials. In a recent paper,[1] we have proposed creation and operation of a modern geophysical data-gathering system to continuously 'harvest' the physical parameters of the atmosphere, the land-surface and the upper ocean in order to support the rational, high-fidelity, supercomputer-based forecasting of the world-wide weather for intervals as long as 2-3 weeks into

[1] E. Teller, C. Leith, G. Canavan and L. Wood, "Long-Range Weather Prediction III: Miniaturized Distributed Sensors For Global Atmospheric Measurements," Proc. of the 26th Symposium on Planetary Emergencies (Erice, Italy, 20-24 August 2001); also UCLLNL Doc. No. UCRL-JC-nnnnnn (2001).

future time. At the core of the proposed system is a constellation of 10^6-10^9 micro-airship platforms – high-tech balloons of about 1 foot diameter – each carrying as its pendant-payload a small atmospheric sampling system to assay the ambient meteorological conditions and to periodically log these observations, time-stamped along with local position and velocity. These high-tech superpressure-balloon-implemented micro-airships drift with the local winds over a program-controlled trajectory in pressure-altitudes (primarily in order to avoid collisions with mountain ranges while circling around the planet and secondarily to avoid otherwise fatal ice-loading in the upper regions of tropical thunderstorms). The interested reader is referred to the above-cited paper for details, as well as system-level considerations of only secondary interest in the present context.

As is summarized from a mass-budget perspective in Appendix A, modern miniaturized sensors combined with a single-chip Global Positioning System (GPS) receiver – which provides 3-D position, wind vector velocity and time – suffice to generate the platform's meteorological data-stream to be logged by its control-computer. Satellite telephony technology allows data retrieval, periodically or at-will, from any platform at any location without creation or deployment of new supporting infrastructure, as well as modification-at-will of each platform's control program. A mass-economized solar photovoltaic energy supply sub-system completes the complement of key technologies comprising each one of these identically-implemented micro-airship platforms. [Supercomputer systems of the scales coming in operation in the USDoE National Security Laboratories – the ASCI systems – are of scale adequate to 'digest' the meteorological data-streams from such constellations and transform them into high-fidelity, all-Earth weather predictions of multi-hundred *billion* dollars/year economic value, as we've noted previously.[2,3] Commercial versions of these supercomputer systems are already being delivered by the Government's suppliers.]

Two sets of modifications of these micro-platforms are proposed to be employed for monitoring weather-pertinent conditions on land- and sea-surfaces. In both modifications, the now-superfluous buoyancy-generating bubble of lighter-than-air gas is eliminated, with the antennae and solar photovoltaic array which were supported by the lower half of the superpressure balloon structure instead being deployed on a rigid plastic sheet over the top of the payload. The sea-surface instrument has appended to its lower end a fiber optic cable-deploying module which, post-deployment, trails out a ~100 meter length of cable periodically studded with a suite of pressure-, temperature-, electrical conductivity- and water velocity-bearing micro-sensors, which cable descends from the surface-deployed module through the local thermocline, monitoring ambient seawater conditions at pre-determined intervals between the local surface and the cable's terminus. The land-surface instrument has the fiber optic cable-deploying module replaced by a rigid soil-penetrating spike whose surface is loaded with local temperature and moisture-sensing sensors for assaying the meteorologically-relevant aspects of the local soil; the entire instrument is bottom-weighted, shock-mounted and aerodynamically configured so as to soil-implant its instrumented spike up to its main body, when field-deployed from aircraft. We have demonstrated in first-order model studies that air-deployed platforms of the contemplated type remain quite randomly distributed throughout the atmosphere, moreover over long intervals[3] – and we confidently anticipate basically similar results from studies of ocean-deployed platforms. [Land-deployed platforms may be as systematically or as randomly deployed as may be desired – they don't migrate, post-deployment.]

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[2] E. Teller, et al., "Long-Range Weather Prediction Enabled By Probing of the Atmosphere at High Space-Time Resolution," Proc. of the 23rd Symposium on Planetary Emergencies (Erice, Italy, 20-24 August 1998); also Univ. of Calif. Lawrence Livermore Nat'l. Lab. Doc. No. UCRL-JC-131601 (1998).

[3] E. Teller, et al., "Long-Range Weather Prediction and Prevention of Climate Catastrophes: A Status Report," Proc. of the 24th Symposium on Planetary Emergencies (Erice, Italy, 20-24 August 1999); also Univ. of Calif. Lawrence Livermore Nat'l. Lab. Doc. No. UCRL-JC-135414 (1999).

This earlier-proposed system is focused on high-fidelity weather prediction out the "chaotic limit," generally believed to lie between 2 and 3 weeks in future-time. It requires exponentially more dense sampling of the atmosphere in both space and time, as the chaotic limit is approached – and thus many millions of micro-airship platforms bearing sensors are required to execute this dense sampling, and thereby to comprise the system.

In contrast, the presently-proposed system requires for its functionality only very long-term averages of meteorological parameters, and thus thousands, rather than millions, of platforms sampling the fluid envelopes and land-surface of the Earth are anticipated to be sufficient – although more detailed analysis of this fundamental issue assuredly is required. [It's reasonably clear that the atmosphere must be sampled somewhere within the 3-30 km horizontal interval in order to forecast weather accurately out to the chaotic limit, whereas it may be sufficient to sample it somewhere within the 100-1,000 horizontal resolution interval, in order to baseline the climate with sufficient accuracy.]

The climate baselining constellation of present interest also requires a significant modification of its ocean-sensing sub-constellation, relative to that of the weather-forecasting one. Since the deep ocean interacts in many significant manners with the atmosphere over the third-century interval of climate-baselining interest, it's necessary to measure its salient geophysical parameters throughout this interval – especially since the ocean stores of the order of years of solar input in heat capacity above its freezing point. Thus, a hundred-fold extension of the fiber-optic cable is required, relative to the thermocline-depth one of interest for long-range weather forecasting; naturally, additional sensors of ambient conditions must be deployed along this far greater length. While not significantly impacting the basic design of the sea-surfaced-based platforms, the cost of the far longer cable bobbin will be discernible in the platform implementation budget, especially as the cable must be repeatedly retractable and re-deployable under program control, as the platform stochastically drifts from littoral to deep-ocean waters, and back again, over its operational lifetime (which is planned to be many years, until unavoidable beaching finally occurs).

The climate baselining system of present interest thus is logically ancestral to the earlier-proposed long-range weather-predicting one, with the notable exception of its deep ocean-probing features. In particular, it can reasonably deploy the 'brassboard' level of long-range weather-forecasting platform technology, rather than having to proceed to the 'steelboard' level for reason of mass-production economies. There is thus less program development time, technical risk and cost-to-initial operational capability implicit in the system of present interest. In the context of major collateral benefits, it seems appropriate to note both its high near-term value for enabling better mesoscale, relatively short-term weather predictions and its great long-term utility in reducing a variety of both technical and program risks for systems aimed at taking high-fidelity, all-Earth weather forecasting out to the chaotic limit. Other collateral benefits are surveyed briefly in Appendix B.

Programmatics. As is sketched in greater detail in the above-cited paper summarizing our present thinking with respect to long-range weather prediction,[1] we believe that it's appropriate to proceed through a series of stages of increasing technological sophistication and deployed size of platform constellation, in order to minimize time, cost and risk prior to attaining full-scale system operational capabilities.

We estimate that a program led by the DoE National Laboratories with expertise in the relevant technologies could attain the first major plateau in capability in a 3-year time-frame, at which point approximately 1000 "brassboard"-level platforms each would be deployed on the land- and sea-surfaces of the Earth, with another ~1000 deployed in the atmosphere at several distinct pressure-altitudes, i.e., with a mean horizontal spacing of the order of 1000 km, corresponding to the atmosphere's largest characteristic eddy-size. The total cost of the associated program would be approximately $95 M, with $10 M, $25 M and $60 M being expended in the 3 fiscal periods comprising this first major phase.

The second major phase of the program logically would involve completion of "steelboard"-level prototyping and associated production and deployment of ~3 orders-of-magnitude more platforms. This phase could be expected to culminate with between 2 and 3 years of execution-effort, depending on the scale of the platform deployment determined to be necessary. The associated cost is estimated to be $200-350 M, i.e., stiff economies-of-scale in serial production of platforms are confidently anticipated, although the non-recurring costs of "steelboarding" and of debugging the large-scale deployment and data-retrieval sub-systems are expected to be quite substantial.

Following this second phase, a third phase of constellation maintenance and data-harvesting is indicated. Operational lifetimes of the order of a single year[4] are anticipated for platforms deployed in/on the planet's fluid envelopes, so that regeneration of most, if not all, platforms on a roughly annualized basis is indicated. We estimate a cost of the order of $75 M/year for this purpose. Employing an 8% discount rate, then, an endowment of ~$0.9 B would suffice to maintain these constellations over the tridecadal interval of intensive measurement required for baselining the climate to contemporary scientific standards. We note that the total cost of this entire program is about a half-year's cost of the present-day U.S. program in "global chance" – which will not baseline the climate to prevailing standards of the meteorological community anytime this side of the indefinite future.

International Aspects. We emphasize the great desirability of the fullest-possible international cooperation in the design, development and operation of the type of system that we propose, which is intrinsically international in nature. Climate baselining is intrinsically a truly global enterprise, just as is long-range weather-prediction. The nature of physical law, as it's expressed in terrestrial meteorology and oceanography, *necessarily* develops baselines of world-wide validity, demanding knowledge of the state of the atmosphere, the ocean and the land-surface from all over our planet. [While baselining via *in situ* measurements of the ocean and – at least arguably – the atmosphere could, in principle, be conducted unilaterally by a single nation within constraints of existing international law, those aspects of climate baselining involving access to land-surface for *in situ* measurements obviously cannot.] Thus, there are few present-day areas of technical endeavor in which international collaboration is more necessary – or in which the large-and-obvious benefits may be more naturally, uniformly and immediately shared among all mankind. The leadership benefits accruing to the nation(s) initiating such efforts seem both obvious and ample.

Conclusions. Policy decisions regarding climate change of any nature or origin – if they wish to claim a scientific basis – must be made relative to an objectively-established and adequately-quantitated climate baseline. It's remarkably challenging to determine such a baseline in the face of the comparatively large amounts of natural climatic variability that may – or may not -- be associated with any long-term change. The established consensus among the meteorological research community is that

[4]Mean lifetimes of 0.5 year were observed for the superpressure balloons of the Global Atmospheric Sampling Program (GASP) in the 1960s, with tropical storm icing being the principal cause-of-demise. [Some GASP balloons which stochastically avoided major lower-latitude storms were observed to attain 2 year lifetimes.] The variable pressure-altitude capabilities of the platforms under present consideration are expected to at least double their mean lifetimes, relative to the GASP systems. We anticipate that irreversible beaching of sea-surface units will be the principal cause-of-demise of the sea-going platform constellation, and thus some rudimentary aeolic-based shore-avoidance capability may be designed into prototypes for field evaluation.

the (local) climate is the time-average of three decades of the (local) weather. Since the human race doesn't have adequately accurate records of the weather over most all of the planet, even today, the scientific community is intrinsically incapable of providing a climate baseline for policy-making purposes.

Seemingly, the sooner such a baseline can begin to emerge from the operation of a necessarily gap-free, whole-planet, high-fidelity geophysical measuring system of the type sketched above, the healthier and less contentious the associated climate-change policy-making process will be. Since the costs in both time and dollars required to create and operate such a system in a reasonably optimal manner appear to be so modest, taking at least the initial steps toward an adequately robust climate baselining system at the present time seems eminently well-advised.

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Appendix A: Some Basic Payload Considerations

Commercial off-the-shelf (COTS) technologies entirely adequate to create the micro-airship-based atmospheric weather-stations of present interest for climate baselining purposes may be purchased; they need not be developed *ab initio*. Similarly, both key system-level capabilities – navigation and telecommunications – may be gained by exploiting extant systems at small-to-zero costs, rather than created *de novo*. For instance, Global Positioning System (GPS)-based sensing of local position and velocity and providing of a highly-accurate time-base, and global-reach bi-directional digital telecommunications for both station control and data-return, via low Earth orbit satellite cellular telephony services (e.g., Worldcom or IRIDIUM) are both available for little, if any, cost-at-the-margin to selected Government communities.

Key components of these modern weather-stations, representative sources for them, their functions and typical masses of them are indicated in Table I.

Payload item	**Source**	**Function**	**Mass (est.), gm.**
GPS chip	Motorola MG2000	3-D location; velocity; time	0.2
Sat-telephony chip-set	Motorola DSP 56690	Telecommunications	0.5
Temperature sensor	Avnet- ADR7418AR	Measure T	0.1
Pressure sensor	SMI-5310-015-AH	Measure P	0.2
Humidity sensor	HyCal HIH-3605-B	Measure H	0.1
Insolation sensor	Edmund H53371	Measure solar flux vs. λ, ϕ	0.1
Droplet spectrometer	LLNL	Measure water drop-size density distribution	1.8
Rechargeable battery	Polystor	Energy storage	1.5
GaAs solar cell-coating & sat-telephony/GPS antennae	Polystor	Energy production; navigation signals; data-&-control communications	1.7
Controller chip-set	Intel	Data/system management	1.1
Memory chip-set	Intel	Data storage (EEPROM, RAM & ROM)	0.8
Wiring, backplane & coverlet	LLNL	Interconnection, mounting & environmental decoupling	1.9
		Total	10.0

TABLE I.

Both land- and sea-surface-based observation stations will necessarily have somewhat higher mass budgets, due to augmentations of their environmentally-specialized sensor suites (e.g., soil moisture and temperature vs. sub-surface distance, and temperature, salinity and current velocity vs. depth, respectively). These will be comparatively incremental in magnitude, however, and no different with respect to their COTS characteristics. Costs of the sea- and land-based sub-constellations of observation platforms will be significantly less than that of the atmospheric one, due to the substantially larger size of the latter.

Appendix B: Other Collateral Benefits

Fundamental advances in the understanding of atmospheric physics and weather prediction can also be expected to provide the calibration now lacking for general circulation models of the Earth's response to altered radiative forcing. Those models are now used to predict the impact of anthropogenic effects on time-scales of decades to centuries, in the regular course of climate-change research. However, the current models do not converge at all precisely to the long-term circulation patterns observed on the Earth when run to long times. Thus, improved understanding of atmospheric physical processes, of real-world mass, momentum and energy flows, and of cloud formation and evolution in atmospheric science could also lead to a real scientific basis for long-term climate impact forecasts.

Also worthy of emphasis is the unique utility of continuously and densely measuring *in situ* the vertical profiles of tropospheric temperature simultaneously with ground- and ocean-surface temperature. Such measurements can be expected to resolve the current discrepancy between long-term temperature trends in the lower troposphere and those made on the Earth's surface.

We also note that this continuously-operating constellation of atmospheric monitoring stations can be expected to diagnose cloud physics in a statistically compelling manner. Such insight could be expected to remove much of the presently-large uncertainty in the indirect aspects of radiative forcing by greenhouse gases, specifically those involving atmospheric water amplification of direct effects.

The R&D program underlying climate baselining could be expected to provide direct information on the atmospheric quasi-turbulent energy spectrum and mesoscale phenomenology needed to refine theoretical estimates of weather predictability.

In addition, the modeling of the biogeochemical cycles of atmospheric trace constituents, e.g., carbon, sulfur, ozone, and aerosols, on a global scale could be realized by addition of appropriate chemical sensors to the micro-airship platforms.

Finally, we note that 'new' atmospheric science learned in the course of greatly improving measurements of atmospheric conditions could also be expected to remove impediments that have reduced the utility of weather models for climate studies and of climate analyses for weather forecasting. Such amelioration of this fundamental logical disconnect would improve the utility of both types of modeling, and thus enhance the overall level of confidence in predictions regarding long-term effects of anthropogenic forcing of the atmosphere, land and oceans.