The unique capabilities of the Global Hawk aircraft for the study of climate changes

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Due to unprecedented extent and flexibility of the coverage that is now attainable both in space and time, stratospheric unmanned aircraft, such as the Global Hawk (GH), offers new opportunities for the study of climate changes. The capability of performing long flights at altitudes close to the boundary conditions of radiative processes, and of following the diurnal variation of chemical species and clouds, make the GH competitive with LEO and geosynchronous satellites, and even capable of new observations that are not possible from satellites.

This paper discusses how the GH can be used to make relevant advancements in most of the issues that are related to climate change studies, such as: Earth Radiation Budget, Water Cycle, Ecosystems and Upper Troposphere–Lower Stratosphere, as well as to the monitoring and control of Greenhouse Gases and Air Quality .

Collaboration between NASA and Italian scientific institutions, within the framework of the U.S.-Italy Cooperation on Climate Change, is providing the opportunity to rapidly deploy new instruments on the GH and to possibly operate the aircraft from an Italian site in the Mediterranean area.

From this area, which is considered highly vulnerable to climate change, meridional transects would allow the crossing of Polar and Sub Tropical Jets, as well as a complete crossing of the Inter Tropical Convergence Zone, while latitudinal ones would follow the influx from Asia and North America. Regions otherwise difficult to access, such as Central Africa and the Tibetan Plateau, could be reached and better investigated. An overview of these new opportunities will be given and discussed.

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Abstract – The new high altitude long endurance unmanned aircraft Global Hawk offers unique capabilities in terms of altitude and range of operation, diurnal coverage and flexibility. It can operate at altitudes close to the boundary conditions of radiative processes, can follow the diurnal variation of chemical species and clouds, can rapidly deploy new instruments with space-time coverage comparable to space-borne ones. These make such aircraft complementary and competitive with satellites.

The collaboration between NASA and Italian scientific institutions offers the opportunity of deploying the GH from the Mediterranean Basin. An overview of these new opportunities will be hereby given and discussed.

Keywords: UAV, Stratosphere, Mediterranean, Climate, Satellite.

1. INTRODUCTION

Scientific research is showing that, in the last twenty years the components of the Earth system are changing and that in the next century our planet shall face the hazard of changes, such as climate warming, rising sea level, deforestation, desertification, ozone depletion, acid rain, and reduction in bio-diversity.

While it is likely that a significant part of the climate change is induced by human activities, its geographic distribution, magnitude and timing (both at the global and regional level) are quite uncertain. Thus, one of the major objectives of Earth sciences in the coming decades is the development of complete and accurate long term measurements of essential climate variables of the atmosphere (such as air temperature and pressure, radiation, water vapour, trace gases and aerosol abundances, cloud properties and precipitation), of the ocean (such as salinity, level, ice, colour, phytoplankton and carbon dioxide abundances) and of the terrestrial surface (such as ground water distribution, snow and ice cover, albedo, land cover).

The complexity of the Earth system, in which on a range of different spatial and temporal scales numerous variables are affected by several different processes, requires that a scientific approach with a comparable structure is developed for addressing the elaborate interdisciplinary problems that exist. Therefore, the implementation of the advanced observing techniques provided by satellites and high altitude aircraft is devoted to improve the quality of the time and space coverage and comprehensiveness of the current measuring network.

A major improvement of our Earth observation capabilities has occurred in the last few years with the deployment of the innovative space-borne instruments of the Earth Observing System (EOS) in the USA and of Envisat followed by the Explorer satellites in Europe. The availability of the Global Hawk (GH), an unmanned high altitude aircraft with an endurance of 31 hrs and a service ceiling of 20000m that can host a payload of 860 kg, offer a major new opportunity for providing new observational capabilities. It can combine the short time deployment of aircraft instruments with the global coverage of satellite instruments. Its flight altitude allows better spatial resolution than a satellite but still maintain a sufficiently broad overview, at a scale relevant for climate studies. NASA has acquired two such high altitude unmanned aircraft to address a variety of Earth science objectives, and Italy has a decade long experience of stratospheric in-situ and remote sensing science missions using the Russian M-55 "Geophysica" high altitude piloted aircraft. There is a common interest in a bilateral cooperative program in climate change science using the GH. We present here a scientific overview of the rationales, measurements and representative missions suggested for a joint exploitation of the GH for climate research.

2. SCIENTIFIC ISSUES

2.1 Earth Radiation Budget

Climate changes are controlled by changes in the energy balance of our planet. A successful management of these changes strongly depends on our capability to detect the variations of the Earth Radiation Budget (ERB).

Existing measurements address separately the variables of this problem with the characterizations of radiative measurements of the short wave (SW) and long wave (LW) outgoing radiation flux; with measurements of the surface albedo of the Earth surface with its two-dimensional scattering properties; with the assessment of aerosols and clouds and their contribution to both the greenhouse effect and the albedo at the top of the atmosphere; with the measurement of the atmospheric composition and of its greenhouse effect; and finally by quantifying sources and sinks of the greenhouse gasses (GHG).

For a reliable attribution of ERB changes it is important to establish a link between the changing properties of the surface-atmosphere system and the changing ERB. To this purpose the measurements that are highly needed are those of the spectrally resolved radiance outgoing towards space. Both Short Wavelength (SW) and Long Wavelength (LW) should be observed, but highest priority is to be given to the LW because the emitted signal contains more information on the state of the system than the signal that is reflected at SW. The GH provides a unique opportunity for early deployment of these new measurements.

The angular distribution of the radiance is another important measurement that is needed for a correct calculation of the irradiance. The angular distribution of the LW radiance can be derived from the observation of the spectral distribution (Palchetti et al., 2008), while for SW scattering effects are anisotropic and the knowledge of two-dimensional scattering field, which evolves as a function of the solar elevation, is essential for the correct calculation of the total albedo. This information cannot be

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acquired for the same pixel from one satellite and a long endurance stratospheric platform is needed for the observation of the two dimensional albedo at the top of the atmosphere as a function of solar elevation.

2.2 Upper Troposphere and Lower Stratosphere Processes

The stratosphere contains the Earth's protective ozone layer, affecting the energy balance of the atmosphere and the ground. Moreover, circulation patterns in the lower stratosphere impact tropospheric weather and climate. Therefore, any attempt to predict future climate must account for stratospheric processes and use their peculiar sensitivity to small changes of trace gases that are chemically and radiatively active, to provide unambiguous markers of climatic change.

Of particular interest is the Upper Troposphere – Lower Stratosphere (UTLS), directly accessible to in situ measurements with the GH. This is a region extremely sensitive to both dynamical forcing and changes in chemical rates, induced by temperature changes, and thus a region with a strong climate sensitivity. In turn, changes in the UTLS impacts climate through the structure of the tropopause and the temperature field, and through transport and mixing with tropospheric short-lived chemical species (Shepherd, 2002)

A series of critical issues for a proper understanding of UTLS processes can be addressed with high resolution chemical and thermodynamic measurements. These are the quantification of the degree of permeability of subtropical and polar mixing barriers, by assessing the sharpness of latitudinal gradient of long lived species; the estimation of the strength of the stratospheric equator-to-pole Brewer–Dobson circulation by recording concentration of species with known tropospheric trends; and the Stratosphere-Troposphere Exchange processes by recording horizontal and vertical gradients of trace gases and their correlations. Moreover, a better assessment of photochemistry and chemical processes can be obtained by the observation of aerosols, actinic fluxes and a full set of chemical families, like HOx, NOx, ClOx, BrOx together with their diurnal variation. The GH would have the unique possibility to follow this diurnal variation and is the sole aircraft able to follow entirely the stratospheric circulation from equator to Pole.

2.3 Ecosystems and Climate

An accurate knowledge of the global carbon cycle has become a policy imperative for this and the forthcoming decades, both globally and for individual countries.

To predict future trends in the global carbon cycle it is thus essential to evaluate how different biomasses are changing the functional processes as a response to global warming, and to understand where carbon pools are located, together with pathways and cycling of carbon.

Under this respect, the main research issues are the ecosystem photosynthetic rate monitoring and its relationship with climate change; the monitoring of the soil behaviour and its modifications; and the monitoring of carbon storage in the ecosystems.

These issues can be tackled by a variety of remote sensing techniques such as hyperspectral sensors, either passive or active fluorescence sensors and Synthetic Aperture Radars (SARs), However, these sensors installed on satellites are characterized by a frequency of observations which is often too low for a research study. The ideal platform should be able to change the frequency of data acquisition, and probably spatial resolution too should be varied following the situation. While some level of monitoring requires weekly or monthly monitoring, others require sub-hourly frequency. For example, for photosynthetic rate monitoring, the possibility of observing the same vegetated area along 24 hours will be of key importance. In this way, a whole daily cycle will be monitored and photosynthesis will be checked over specific areas. The opportunity offered by the GH is unique because of its endurance, its payload, and its flight altitude.

2.4 Greenhouse Gases.

The knowledge of how the load of greenhouse gasses (GHG) in the atmosphere is changing and which are the causes of these changes is crucial for the assessment of the possible climate evolution and of the effectiveness of the mitigation actions. A few ground stations are providing long term records of in-situ concentration of GHG and several space instruments (e.g. IASI, AIRS, TES, SCIAMACHY, OMI) can measure their column density at a global level. Furthermore in the next few years two important new instruments (OCO and GOSAT) that are fully dedicated to the monitoring of GHG will be launched.

Future challenges are the development of more precise measurements of the geographic distribution of GHGs in the boundary layer so that sources and sinks of the GHG can be derived, as well as an improved knowledge of water vapour in the upper troposphere, which is poorly determined with the existing measurement techniques while being very important for its direct (FIR emission) and indirect (cirrus formation) contributions to the radiation budget.

These observation challenges are best pursued with satellite instruments, because of their global coverage. However, aircraft observations can contribute significantly to the development of the observation capabilities with the early utilisation of instruments that are not yet ready for space operation. This is in particular the case of active instruments which, because of their new technology and high power consumption, cannot be readily deployed on a space platform.

2.5 Air Quality and Climate

Air quality and climate are strongly interlinked. Human activities emit a wide range of pollutants that change atmospheric composition and that can severely affect air quality at the local and regional scale, thus impacting the health of the population and the ecosystems. At the same time, anthropogenic emissions can also affect climate. Direct effects include emission of aerosols that can change the Earth's radiation balance; indirect effects include changing the atmospheric lifetime of GHG. In turn, climate change can affect air quality in different ways, e.g. higher temperature may mean higher plant emissions of biogenic volatile organic compounds (VOC) which would increase tropospheric ozone production which affects human health, natural ecosystems and agriculture productivity.

It is well known that aerosols contribute to poor air quality. On the other hand, aerosol primary emissions and secondary production in the troposphere have also an effect on climate, through their interaction with radiation and their ability to act as cloud condensation nuclei for the formation of clouds. Another link between air quality and climate is the recent trend of urbanization worldwide and the rapidly increasing number of the so called megacities, that will lead to serious issues in local air pollution, in turn causing significant local and regional consequences for human health and crop production. Moreover, emission of pollutants from these concentrated population centres can affect atmospheric composition and thus climate at the continental and global scale. Air pollution processes evolve on a time scale of hours at the most and the study of such processes from satellites would imply the presence of geostationary platforms which are presently not available for this purpose and have a limited spatial resolution. The great advance of the GH in this context would be its long endurance which can allow observations of selected areas over the diurnal cycle of pollution.

2.6 Water and energy cycle

Life on Earth depends upon the continuous cycling of water between oceans, continents and the atmosphere. Precipitation, the primary mechanism for transporting water from the atmosphere back to the Earth's surface, is the key physical process that links weather, hydrological cycle and climate. Changes in precipitation regimes and/or in the frequency of extreme weather events are of great potential importance to life on the planet. Precipitation is affected primarily by atmospheric dynamics, but it is also influenced by cloud microphysical processes associated with aerosol properties which are primarily responsible for cloud drop and ice crystal formation.

Recent studies have suggested that the increased aerosol loading due to anthropogenic activities may have changed the energy balance in the atmosphere and at the Earth's surface and altered the water cycle in ways that make the climate system more prone to precipitation extremes. However, present understanding of the interplay between aerosol, clouds and precipitation is still rudimentary (Rosenfeld et al., 2008) and a recent survey (Zhang et al., 2007) has shown that there is often poor agreement between model predicted precipitation trends and the measured ones.

While the knowledge on warm rain processes is reasonably advanced, much remains to be learned concerning ice formation mechanisms in clouds which remain one of the critical issues in aerosol-cloud-precipitation interaction. Remote sensing instrumentation (radars, microwave radiometers, lidars) is a primary tool to address this issue from a high-flying platform, to improve the understanding of the thermodynamics, dynamics, and microphysics of clouds, by measuring the evolution of their 3-dimensional thermodynamical, dynamical, and microphysical structures and the 3-dimensional structure and evolution of the aerosol content. The long endurance of the GH will allow the study of cloud systems extended over very large areas and follow repeated cloud cycles.

2.7 Atmospheric dynamics

General Circulation Models (GCM) have to tackle with the fact that baroclinic conversion - namely the physical process that transforms, at large scale, heat fluctuations into atmospheric organized motions - depends in a sensitive way on the vertical structure of the atmospheric fields. In models, the vertical representation of the atmosphere is in most cases limited to few discrete levels, ever fewer representing the core of atmospheric motions. Nevertheless, in the last 10 - 15 years, modellers have concentrated their efforts on the increase of horizontal resolution, with the purpose of improving the regional details in the representation of the current climate and its future changes, despite the potentially negative impact of a reduced vertical resolution in the modeling. That argument has never found a complete development, and one of the possible reasons was probably the lack of conclusive measurements. Under that respect, a decisive development could be provided by radio - occultation GPS measurements that guarantee a high vertical resolution for the temperature field between approximately 5 and 15 km in altitude. The well known weak point of these measurements is the low horizontal resolution which is surely improved when observations are carried out from an aircraft platform such as the GH. Moreover, if the payload also includes downward pointing radiometers for the measurement of temperature and water vapour profiles, a better knowledge of the weighting mechanisms in forming the averaged measurements along the horizontal path can be reached. The possibility to carry out such measurements from the GH platform could improve knowledge and algorithms in this field.

An additional, very important scientific objective consists in determining the spectra of turbulence in the mesoscale range, which was formerly measured with thermometers and accelerometers on board of commercial airplanes. An associated, fundamental problem is that of understanding the relative role of turbulence and waves in that range; additional measurements by profilers may help disentangling waves and turbulence.

2.8 Global Hawk and satellites

More generally, the GH provides an important tool for the development of advanced technology and validation of satellite observations. In fact, innovative instruments can be quickly deployed on the GH where they can operate until proven instruments are developed for the subsequent long term satellite observations. Their coverage would be as good as that of space-borne ones in terms of seasonal and geographic monitoring and even better than space-borne instruments in terms of combined angular and time observations. Moreover, the validation of the technique and retrieval algorithms from a stratospheric aircraft, as a precursor for a foreseen satellite mission, would be of paramount importance for the assessment of the technique and of its scientific outcomes.

3. MISSION OPPORTUNITIES WITH THE GLOBAL HAWK FROM THE MEDITERRANEAN

3.1 The Mediterranean Area

Regional consequences of global climate change are especially affected by the large uncertainties that arise, when trying to provide predictions on changes in precipitation patterns, length of growing seasons, and the severity of storms. Not withstanding these high levels of uncertainty, it is to be stressed how Europe, because of its geographical position, seems to be prone to receive the full blow of undesired climate modification. In fact the several thousands of kilometres of built-up coastal lands make the continent vulnerable to sea rise. The prevalent weather patterns of its southern regions, which are predominantly positioned in the Mediterranean basin, make the latter at risk if the basin fluxes are modified or the descending branch of the Hadley cell is displaced northward, enhancing summer droughts to the point that a full scale desertification process becomes possible. The economies which are present in Europe are sources of pollution which, because of changes in prevailing wind patterns, may cause modification of pollutant distributions in an unpredicted as well as undesirable fashion.

A good spatial resolution, achievable only from high altitude aircraft platforms, is essential for studying areas of particular complexity at the mesoscale, such as the Mediterranean one, which is still unsatisfactorily reproduced in the large scale models or satellite measurements. Finally, apart from the interest the region has in itself, other areas not accessible with other conventional high altitude aircraft due to logistical limitations would be accessible by a GH based in the Mediterranean. Some observational activities based on the Mediterranean region are hereby outlined.

4.2 Mediterranean Medicanes

Some intense Mediterranean mesoscale convective storms do not have the classical baroclinic origin, but rather form and evolve into warm core structures deriving their energy directly from the warm sea surface similar to tropical cyclones. These tropical-like storms often have been referred to as Mediterranean hurricanes, or more prosaically "Medicanes" (Fita et al., 2007), although they are smaller and weaker than their tropical counterparts, and dissipate faster (typically within 2-3 days). Understanding the nature and physical processes of these extreme precipitation events will aid in the ability to better forecast Medicane-type storms and their potentially destructive effects on the Mediterranean coastal regions. The observational payload of a GH flying above the Medicane, should include the 3-dimensional thermal, moisture, velocity, and microphysics structures, and the 3-dimensional aerosol distributions. The proposed payload should then consist of a dual-frequency Ku-band / Ka-band (14/36 GHz) Doppler radar system; a conically scanning, multi-frequency (10-183 GHz frequency range) microwave radiometer, that would obtain horizontal and vertical information on liquid water path and ice water path; a volume-imaging Lidar for determination of the detailed 3-dimensional properties of the aerosol. This would partly emulate the payload of the Core Satellite of the future NASA/JAXA Global Precipitation Measurement mission (Smith et al., 2007).

4.3 Deep convection in Central Africa

Central Africa is where the most energetic deep convection occurrence peaks, and where one of the major CO_2 ground sinks is found. Despite its importance for studying the effect of deep convection of stratosphere to troposphere exchanges, it is one of the most heavily under sampled regions of the world. GH flights, to be performed during the boreal winter season from the Mediterranean, would allow the complete crossing of the Sub Tropical Jets and the Inter Tropical Convergence Zone allowing the study of their effects on tropospheric and stratospheric transport and interhemispheric differences in stratospheric tracers. Once over Central Africa, flight time may still be dedicated to probe individual convective events, as the aircraft can be directed to a region of intense convection in real time, by satellite nowcasting. The payload of this mission would include, as a baseline, in-situ sensors to measure stratospheric trace gases like O_3, CO, CH_4, H_2O, N_2O, CO_2 as well as Temperature, Pressure and Particle sensors.

4.4 The East Asian Monsoon

An assessment of the role played by the East Asian Monsoon system – suspected to be fundamental - is needed to quantify vertically the fluxes of trace species in the TTL and into the stratosphere, and to track the zonal transport and intrusion of air from South East Asia, through the Bay of Bengal, Arabic Sea, Sahara, and its spreading from the Sahel to the south Mediterranean.

In particular, the Tibetan Plateau seems to play a great role in injecting tropospheric air into the stratosphere, to be redistributed zonally along the tropical belt. Unfortunately, due to logistical constraints, in-situ observations from that region are lacking and satellite data are not suitable to assess the proper representation of processes in the models, due to their poor vertical and horizontal resolution.

Objective of the GH flights – to be performed during the boreal summer season – would be to execute east-west transects and, once in the east Asian monsoon region, north-south transects. The transects would be conducted at constant altitude between 15-20 km with, possibly, dives at midpoints to acquire vertical profiles of tracers. The basic payload should be as outlined in Sect. 4.3.

5. CONCLUSION

Reliable observations and reliable diagnostics are required for successful political decisions. The availability of a powerful new platform, such as the GH, which fills the gap from the local to the global scale, will help in unraveling key scientific issues and assessing the anthropogenic impact on climate. Understanding the nature of the various physical processes will improve our ability to better forecast their potentially negative effects and to define mitigation and adaptation strategies.

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