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Advanced Thermosphere Modelling for Orbit Prediction

ATMOP

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2	Centre National de la Recherche Scientifique	**CNRS**	France
3	Collecte Localisation Satellites	**CLS**	France
4	Met Office	**MET**	United Kingdom
5	Centre National d'Etudes Spatiales	**CNES**	France
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1. INTRODUCTION

1.1. Purpose of the Project

The “Advanced Thermosphere Modelling for Orbit Prediction (ATMOP)” research project aims at building a new thermosphere model with the potential to spawn an operational version. It will enable precise air drag computation, which is mandatory for improved survey and precise tracking of objects in Low Earth Orbit (LEO) and the initiation of appropriate measures to minimise risks to satellites (tracking loss, collisions) and ground assets (re-entry zone).

With thousands of objects orbiting the Earth and the majority of them in LEO, survey and tracking of the larger specimens among these objects becomes an indispensable task for space agencies and satellite operators. Orbit determination methods are used to predict the trajectory of the objects hours to days ahead, and the estimated orbits are updated each time an object is tracked. For the sake of operations, it is obvious that an accurate orbit prediction is necessary to locate an object in time and space. To minimise the risks coming from space objects, accurate knowledge of the orbits of all objects in space that can pose a risk on space (due to possible collisions) or ground assets (due to re-entry objects) is needed. This requires an accurate thermosphere model.

Despite the presence in Europe of one of the three groups that have the capability to develop and maintain an operational semi-empirical thermosphere model (CNES/CNRS, the other two are in the US), and of one of the world’s leading teams in the field of physical modelling of the atmosphere (UCL), Europe has currently neither a near-real-time thermosphere prediction model nor operational services to provide regular thermosphere nowcast and forecast.

The ATMOP project is designed to fill this gap through

- Defining and assessing new proxies to describe the external forcing of the thermosphere;
- Developing an advanced semi-empirical Drag Temperature Model (DTM) that meets the requirements for operational orbit computations;
- Improving physical modelling of the thermosphere to assist the development of the advanced DTM and of a global physical model with data assimilation capabilities, which may ultimately become the successor to semi-empirical models;
- Developing schemes for near-real-time assimilation of thermospheric and ionospheric data into an advanced predictive DTM and into the physical Coupled Middle Atmosphere-Thermosphere (CMAT2) model.

The updated semi-empirical DTM that will be constructed in the framework of the ATMOP project will be based upon the most comprehensive database available to researchers. It will in particular include densities inferred from accelerometers onboard CHAMP and GRACE, which supplied high quality thermospheric density data over almost one solar cycle, including years of high geomagnetic activity (2003) and exceptional low solar activity (2008 -2010).

The thermosphere can vary rapidly and significantly in response to solar and geomagnetic activity (space weather), i.e., accurate orbit prediction requires accurate space-time nowcast and forecast of the thermosphere. The first and almost immediate external forcing of the thermosphere results from the direct interaction between EUV radiation and the neutral atmosphere: it predominantly drives the medium and long-term evolution of the thermosphere, (on time scales of days to years). The second forcing process results from the solar wind impact on the magnetosphere and its coupling to the ionosphere and the complex interaction between the neutral and ionized components of the Earth atmosphere: it mostly drives short-term changes in response to rapid variations in the solar wind conditions, and the associated geomagnetic activity. The latter forcing process can be described in terms of energy deposition in the auroral zone and subsequent heat transport to mid and low latitudes. Because of the short time lag between geomagnetic forcing and the thermosphere response only rapid thermosphere modelling can be efficiently used for satellite orbit computation and debris surveillance.

The ultimate objective of our project is to perform precise thermosphere modelling within a time delay that will eventually enable operational thermosphere nowcasting and forecasting and which we call ‘near real-time’ modelling.

1.2. Scope of the Document

This document provides a summary of the main scientific objectives of the ATMOP project, a description of the tasks to be done for their achievement, and the list of deliverables.

1.3. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are the following ones:

Table 1: Table of Acronyms and Abbreviations

Acronym	Meaning
ATMOP	Advanced Thermosphere Modelling for Orbit Prediction
CDTI	Ministerio de Ciencia e Innovación-Spanish Government-
CHAMP	Challenging Minisatellite Payload
CMAT2	Coupled Middle Atmosphere Thermosphere model
CTIP	Coupled Thermosphere Ionosphere and Plasmasphere
DA-GA	Data Assimilation – Global Analyses
DA-NRTP	Data Assimilation – Near Real Time Prediction
DTM	Drag Temperature Model
ESA	European Space Agency
ESOC	European Space Operation Center
EU	European Comission
EUV	Extreme Ultra Violet
FP	Final Presentation
GAIM	Global Assimilation Ionospheric Model

Acronym	Meaning
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IGY	International Geophysical Year
IPR	Intellectual Property Rights
JB2008	Jacchia Bowman 2008
KO	Kick-off Meeting
LEO	Low Earth Orbit
MGT	Management Meeting
MSIS	Thermospheric model based on Mass Spectrometer and Incoherent Scatter data
NEO	Near Earth Objects
NRLMSISE	Naval Research Laboratory MSIS MSIS Extended version
NRT	Near-Real Time
PA	Project Administrator
PAM	Product Assurance Manager
PC	Project Coordinator
PL	Project Leaders
PM	Person-Month Plenary Meetings
QA	Quality Assurance
QAC	Quality assurance coordinator
R&D	Research & Development
SC	Steering Committee
SCM	Steering Committee Meeting
SOTERIA	Solar-TERrestrial Investigations and Archives
SSA	Space Situational Awareness
SVN	SubVersioN
TL	Task Leaders
TLE	Two Line Elements
TWM	Technical Working Meeting
US	United States
UV	Ultra Violet
UT	Universal Time
WP	Work Package

Acronym	Meaning
WPL	Work Package Leaders

1.4. Related Documents

Table 2: Applicable Documents

Ref.	Code	Title	Date
[AD.1]	ATMOP-GA	ATMOP Grant Agreement	
[AD.2]	ATMOP-DoW	ATMOP Annex I - "Description of Work"	2010-08-13

Table 3: Reference Documents

Ref.	Reference Documents	Date
[RD.1]	N/A	

2. CONCEPT AND PROJECT OBJECTIVES

Drag affects satellite attitude , orbit decay and space debris tracking . Computing drag forces requires modelling of both the aerodynamic properties of the object and the properties of the thermosphere (density and wind) at the object location. The former is an engineering problem while the latter is a fundamental research issue which falls thematically into the FP7 Research and Technology Programme and will be addressed by ATMOP. For a given object configuration, drag changes are mostly caused by varying solar and geomagnetic activity. Understanding and predicting their impact is of major importance for Low Earth Orbiting (LEO) satellites and for space debris. The model and the products developed within ATMOP will have the potential to be adopted by national and the European space agencies for subsequent conversion into an operational thermospheric drag model. Although ATMOP focuses on a specific problem, the outcome of the project will benefit a larger user community that is affected by the impact of solar irradiance and geomagnetic activity on the upper atmosphere.

The thermosphere, that part of the Earth's atmosphere extending from about 100 km up to 1000 km above the ground, hosts thousands of LEO objects. At thermospheric altitude, the gas is rarefied but sufficiently dense to exercise measurable frictional forces (drag) on moving objects.

The air density – and consequently the drag – exhibits a regular spatio-temporal pattern that is controlled by the diurnal and annual variations of solar illumination and by global wind patterns and which is nowadays well described by physical and semi-empirical models. It also has a semiannual variation[1] with maxima occurring in April and October, and minima occurring in January and July. Bowman et al. (J. of Atmos. Sol-Terr. Phys., 2008), using data from 28 satellites covering a period of some 40 years, successfully constructed a model for the semiannual variation. The main finding of their study is that the amplitude (changing 60-250% from solar minimum through maximum) and phase of the semiannual variation is highly correlated with solar activity.

In addition to the regular pattern, the thermospheric air density undergoes irregular spatio-temporal variations that result from solar activity ('solar weather') which is at the origin of 'space weather' – the physical and phenomenological state of our space environment and its (primarily solar driven) perturbations. Space weather in the thermosphere manifests itself as irregular, transient deviations of gas temperature and density from their quiet-time levels. For instance, when energy of magnetospheric origin, mostly in the form of Joule heating, or from the lower atmosphere, is suddenly transferred to the thermosphere at high latitudes, an extended wave front propagates outward from the source region. This disturbance is referred to as a travelling atmospheric disturbance (TAD), which in turn causes periodic advection and compression of the plasma in the ionosphere called travelling ionospheric disturbance (TID). Travelling disturbances and related gravity waves cannot be modelled with a statistical semi-empirical model because they depend on dynamical conditions. Numerical models can be successful at least qualitatively.

In the wake of intense solar activity, the air density and wind field at a given location and altitude can experience very large changes which induce significant local variations of drag forces. For instance,

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[1] The semiannual density variation was first discovered in 1961 by Paetzold and Zschorner, who observed a global density variation from analysis of satellite drag data (Paetzold, H.K. and Zschorner, H. (1961), The Structure of the Upper Atmosphere and its Variations after Satellite Observations, Space Research II, 958. North-Holland Publ. Co., Amsterdam).

during the severe geomagnetic storm of October 2003 near 410 km altitude and at low latitudes, the air density exhibit enhancements of 200-300% and the winds shift from near zero values to westward values of order 200 to 250 m/s.

Survey and tracking of LEO objects thus becomes an indispensable task for space agencies. For objects in LEO, orbit determination methods are used to predict their trajectory hours to days ahead and to apply corrections on each occasion when the object is observed and tracked. This requires accurate orbit prediction in order to find the object at the right time and place and to neither waste time and resources on searching for an object nor lose connection with the object entirely.

> *The primary objective of the ATMOP project is the development of an advanced semi-empirical Drag Temperature Model (DTM) that has the potential to be adapted for near-real-time operation and is sufficiently accurate to meet the requirements set by space agencies for orbit computations.*

Satellite orbit changes caused by atmospheric drag are not to be underestimated. Increased atmospheric drag due to space weather events has resulted in changes in the predicted position of LEO spacecraft such as SPOT (at about 800 km altitude) by as much as 8 km in one day. Drag in the same way affects space debris, the precise tracking of which is affected during space weather events. The German CHAMP (CHAllenging Minisatellite Payload) satellite was launched into a circular LEO with an initial altitude of 454 km. The altitude decreased because of thermosphere drag, due to both regular (predictable) and irregular forces, the latter being manifestations of space weather. The loss of altitude amounted to more than 100 km over 9 years even though three orbit raising manoeuvres using on-board gas thrusters were performed.

Orbit prediction is not only required for tracking an object, it is also necessary to initiate proper countermeasures when collisions between objects are likely to occur. Although the space environment occupies a huge volume and the objects are small, collisions do happen. A notable recent example is the collision of one of the US Iridium satellites with a Russian Federation satellite and their subsequent total destruction.

Another important operational issue requiring thermosphere modelling concerns the surveillance and forecasting of trajectories for decaying objects that eventually enter the lower and denser atmospheric layers. The object trajectory change depends on the thermosphere density at its precise location, i.e., on altitude, latitude, and longitude, all of which change rapidly during the re-entry process. In consequence, the requirement to take risk reducing measures in order to avoid re-entry over populated areas requires accurate 3-D modelling of the thermosphere and 3-D forecasting of the object trajectory in the geographic sector concerned.

The European Space Agency (ESA) has recognised the vulnerability of space assets due to diverse types of perturbations of the space environment and initiated, in cooperation with several national European governments, agencies and interested parties, the Space Situational Awareness (SSA) programme which is expected to run over many years. Survey and tracking of space objects is explicitly stated as one of the tasks to be addressed by the SSA programme, and it is specifically requested that geomagnetic and solar indices are collected and archived for the purpose of satellite drag calculation. The SSA programme further suggests that forecast models of geomagnetic and solar indices are developed with the objective to enable drag forecasting. The work proposed for ATMOP is thus highly relevant to SSA but complementary because it addresses development of assets for thermospheric modelling, data assimilation and drag calculations intended (beyond the project lifetime) to upgrade the current generation identified by the SSA preparation phase.

Survey and tracking of LEO objects is a task that involves more than geodetic and engineering tools, it involves solar and space science and aeronomy because the thermosphere is subject to external forcing. Two principal sources of external (space weather) forcing of the thermosphere have to be considered when building a realistic and accurate thermosphere model, solar radiation forcing (termed “EUV forcing”) and electro-magneto-mechanical forcing (termed “geomagnetic forcing”). Irregular variations of both types of external forcing result from solar activity and are thus space weather effects.

The first and almost immediate external forcing of the thermosphere results from the direct interaction between EUV radiation and the neutral atmosphere: it is the so-called “EUV forcing”, which is strongly wavelength-dependent. The energy deposition mostly takes place below 200 kilometres of altitude: as the radiation wavelength becomes longer, penetration into the atmosphere is deeper and thus the altitude of the energy deposition is lower. The second forcing process is the so-called “geomagnetic forcing”. It results from the solar wind[2] impact on the magnetosphere and its coupling to the ionosphere and the complex interaction between the neutral and ionized components of the Earth atmosphere. EUV forcing predominantly drives the medium and long-term evolution of the thermosphere (on time scales of days to years) whereas geomagnetic forcing mostly drives short-term changes (time scales of minutes to days), in response to rapid variations in the solar wind conditions, and in the associated geomagnetic activity.

Different altitude domains of the thermosphere have different molecular and atomic compositions and densities, but they are collisionally coupled. In the lower part, below some 200 km altitude, the neutral gas is collisionally coupled with the ionised component which in turn is strongly controlled by electromagnetic forces. Electromagnetic forces are far reaching and complex, and they have significant impact on the Earth’s space environment. They include the interaction of the solar wind with the Earth’s magnetosphere and the coupling between the magnetosphere and the ionosphere the latter of which is a two-way process – the magnetosphere acts on the ionosphere and imposes magnetic and electric fields and currents, and the ionosphere modifies the magnetospheric electric field and supplies the magnetosphere with charged particles.

The influence of the solar wind-magnetosphere-ionosphere coupling on the thermosphere can be described in terms of energy deposition in the auroral zone and subsequent heat transport from the auroral zone to mid and low latitudes. The preponderant term of the auroral energy deposition, the Joule heating, manifests itself as geomagnetic activity because both the Joule energy deposited in the auroral thermosphere and the magnetic activity are derived from the high-latitude ionospheric current system. It is composed of field-aligned currents closed by horizontal Pedersen currents (which are responsible for Joule heating) and the often much stronger self-closed horizontal Hall currents the largest of which are the auroral electrojets.

The time lag between the energy deposition at auroral latitudes and the corresponding thermosphere response at mid latitudes is of the order of a few hours. Because of the short time lag between geomagnetic forcing and the thermosphere response only rapid thermosphere modelling can be efficiently used for satellite orbit determination and debris surveillance.

> *The ultimate objective of the project is to perform precise thermosphere modelling within a time delay that will eventually enable operational thermosphere nowcasting and forecasting and which we call ‘near-real time’ modelling.*

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[2] The solar wind is a stream of predominantly protons and electrons which are continuously emitted from the Sun and reach the Earth typically within 1-4 days.

2.1. Development in Semi-empirical Modelling of the Thermosphere

Today, operational drag modelling is done using semi-empirical thermosphere models that use proxies to describe the solar and geomagnetic forcing of the thermosphere. Most of them are based upon thermospheric temperature and density data acquired before the year 2000[3] . In France, CNES and CNRS teams have developed and maintained the only European semi-empirical thermosphere model which is nowadays in use, the Drag Temperature Model (DTM). Note that the state of the art physical models are still not sufficiently accurate to serve operational purposes, and they still require prohibitively long computer run time.

After the launch of the CHAMP satellite in July 2000 and of GRACE in 2002 new measurements of the total mass density of the thermosphere have become available, thanks to the high precision of the accelerometer data provided by these missions. The CHAMP measurements have been used to study the statistical properties of the thermosphere density global distribution and its response to geomagnetic activity forcing. These studies have underlined the inadequacy of the semi-empirical thermosphere models used nowadays for estimating the thermosphere density, but especially so during space storms. The errors of the models severely affect space geodesy (e.g. precise positioning of Doppler ground stations) and precise orbit computation.

Only three groups (two in the US and CNES/CNRS in Europe) have the capability to develop and the experience to update and maintain a semi-empirical model; and none has yet taken full advantage of the high-quality density data provided by the CHAMP and GRACE missions. So far, only a preliminary version (not published) of the CNES DTM model has assimilated accelerometer-inferred densities. The updated semi-empirical DTM that will be constructed in the framework of the ATMOP project will be based upon the most comprehensive database available to researchers (see section 3.2.2). The completeness in terms of temporal and geographical distribution of the density data (i.e., data at all altitudes, latitudes, and local times, covering at least a solar cycle) is essential to the objective, since a semi-empirical model basically is only valid under conditions for which a sufficient amount of data has been assimilated.

Semi-empirical models rely on proxies. Proxies are parameters that are defined either as measurements of only a part of the full range of parameters, which have influence on the system, or as signatures of the magnitude of parameters that influence the system but are not directly measured. In order to meet the prime objective of ATMOP, the construction of a significantly more accurate semi-empirical thermosphere model, it is necessary to revisit the question of the solar radiation and geomagnetic proxies used to describe the external forcing of the atmosphere. The routinely used proxies do not take advantage of the present state of the art in the solar spectrum and geomagnetic routine observation and of the present understanding of the physical processes that force the thermosphere.

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[3] CNES has access to density data. The CHAMP and GRACE data are retrieved from the ISDC server in Germany and processed by CNES. Densities are subsequently derived from the accelerometer measurements. GOCE and Swarm data, via ESA Announcements of Opportunities, will be processed in the future. Satellite laser ranging data, available through the International Laser Ranging Service, are processed by CNES, using the perturbation method, and mean densities (low spatial and temporal resolution) are derived. The NORAD two-line elements, i.e., mean osculating element data, must be downloaded from (http://celestrak.com/NORAD/elements/).

> *An important task of the ATMOP project is the definition and evaluation of new proxies to describe Extreme Ultra Violet (EUV) and geomagnetic forcing which take advantage of the present state of the art in observational and data analysis capabilities.*

All semi-empirical models use the solar radio flux at 10.7 cm (the F10.7 index) or variants thereof as a proxy for the solar EUV forcing. The JB2008 model in addition uses several proxies that incorporate information from other sources, and in particular the EUV flux in the 26-34 nm band from SOHO. All semi-empirical models also use the 3-hour Kp planetary geomagnetic index to characterize the geomagnetic forcing; JB2008 also uses the Dst index during intense geomagnetic storms. EUV and geomagnetic data are public.

These proxies take advantage neither of the present state of the art in routine solar spectrum and geomagnetic observations nor of the present understanding of the physical processes that drive the thermosphere forcing. For example, recent results show that the solar irradiance in different spectral bands of the EUV behaves remarkably similar, which means that not all spectral bands need to be measured in order to properly reconstruct the spectral variability. From a statistical viewpoint, however, defining the spectral bands that provide the best description of the spectrum, and those that best describe the variability of the thermospheric density, are two different problems. Here we want to focus on the second one, which has received very little attention so far in the literature. On the other hand, the lack of geographical resolution (Kp and Dst are planetary indices) and the poor Kp time resolution (Kp is a 3-hour index) make it necessary to introduce new geomagnetic proxies with higher geographical and temporal resolution. Designed at the end of the 1940s, Kp in fact does not take advantage of the present availability of digital magnetic recordings at most of the geomagnetic observatories, which makes it possible to derive indices with a higher temporal resolution.

The ATMOP project will take one further step: in addition to the use of proxies we will devise an assimilation scheme which makes it possible to assimilate observed density data and use them in combination with the new solar and geomagnetic indices. This procedure together with an improved modelling algorithm will result in the least-biased mean (i.e., a stationary thermosphere without inter-annual variations) DTM model (see Section 2.3 for more details).

The selection of the best possible input parameters (proxies) for the empirical model under consideration may be achieved by trial and error, but it is more useful to let physical considerations guide the development of an empirical model, which then results in a ’semi-empirical model’. One of the tasks of the ATMOP project aims at providing physical understanding of and guidance for selecting the best available geomagnetic proxies

The goal of this endeavour is to better understand, by means of as comprehensive a set as possible of multi-point space borne and ground-based observations, the relation between external electrodynamic drivers and the response of the thermosphere. The results will aid in refining the semi-empirical model and will help to clarify when and why the empirically selected proxies work best and which physical conditions limit their application. One however should keep in mind that electrodynamically driven density irregularities are by their nature very variable and depend on dynamical conditions. This makes it difficult to include anything useful on irregularities in statistical semi-empirical models, except perhaps to provide the error bars that irregularities might cause under different conditions. (e.g., try to identify the major causes of irregularities and then calculate the maximum effect they would have on atmospheric density at a given location for specific strengths of the disturbing forces.)

EUV forcing of the thermosphere is a virtually direct process while geomagnetic forcing is an indirect process in the sense that solar activity modifies thermospheric temperature and density via a complex chain of events. Solar energy other than electromagnetic radiation is conveyed to the Earth's environment via the solar wind, superimposed clouds of mass ejected from the solar corona, and energetic particle streams (very high energy protons and electrons which are emitted from the Sun in a burst-like fashion and typically reach the Earth within tens of minutes to several hours). These manifestations of solar activity deposit energy in the Earth's magnetosphere where it is partly stored and partly dissipated, not least in the upper atmosphere, thereby affecting both the ionised and the neutral components.

In order to understand and assess the behaviour of the semi-empirical model in an anomalous situation it is necessary to investigate the physical processes, specifically the electrodynamic coupling between magnetosphere, ionosphere and thermosphere, under the prevailing conditions. An anomalous situation is a situation that occurs rarely and does not provide for a sufficiently large statistical sample, which causes empirical models to have large uncertainties or to be not at all applicable in this situation. A further complication derives from the fact that several very energy-intense processes are known which operate on scales of tens of meters to a few kilometres. Among them we find electric currents in the polar cusps and in auroral forms. Their impact on the state of the thermosphere is not known, mainly because of the much larger scale sizes considered in thermospheric modelling.. Global models such as DTM and CMAT2 cannot account for such small-scale phenomena other than in a statistical sense because they are below the spatial resolution of the model. Small-scale structures may, however, have a significant impact on the local modification of the thermosphere. The effect of electrodynamic processes on small-scales on the thermosphere will be investigated in the ATMOP project.

The specific investigations described above will be carried out mostly in the form of case studies. The results will have bearing for semi-empirical as well as physical modelling. Indeed, a major task within the ATMOP project addresses the further development of a comprehensive physical model of the atmosphere-thermosphere system with the objective to suggest and assess potential improvements to the semi-empirical model.

2.2. Developments in Physical Modelling of the Thermosphere

The ATMOP project will take advantage of the presence in Europe of one of the world leading teams in the field of physical modelling. A numerical model of the Earth's thermosphere and ionosphere has since 1981 been under continuous development at the University College of London. This has led to a range of models culminating in CMAT2 (Coupled Middle Atmosphere Thermosphere model) which draws on the expertise gained from the better known CTIP (Coupled Thermosphere Ionosphere and Plasmasphere) model but which takes its lower boundary down to 15km altitude. CMAT2 works by solving the Navier Stokes equations of energy, momentum and composition on a latitude, longitude, pressure level grid. Electrodynamic coupling is modeled in CMAT2 as a self-consistent coupled ionosphere-thermosphere system, and the major coupling effects are included. The main limitation to its resolution and accuracy is due to the limited observational information about the drivers.

The CMAT2 model will be used to assist the development of the improved semi-empirical DTM thermospheric drag model by evaluating possible improvements and changes based on physical considerations and experiences made with running the CMAT2 model under different input and boundary conditions. We will for instance address the semi-annual variation, and investigate the possibility to have it included in a semi-empirical model. There have already been a number of attempts to explain the semi-annual variations in the ionosphere – and by inference the thermosphere – using the CTIP model and its variants. Such studies provide valuable insight into compositional and energetic variability which might well be parameterised or turned into a simple algorithmic addition to a semi-empirical model. We will address it too in the numerical modelling by trying out potential mechanisms. We will also address TIDs using CMAT2, concentrating on investigating whether the numerical model supports the suggestion that one link between solar variation and climate may be by aurorally generated waves propagating downwards and to mid-latitudes where they affect tropospheric cloud formation. Although such studies are unlikely to provide improvements to the semi-empirical model being developed, they will inform considerations of the resultant likely error bars under different conditions.

The CMAT2 model will also be used to build capability for ionosphere / thermosphere data assimilation based on a global physical model, which may ultimately become the successor to semi-empirical methods. The advantage of a well-functioning physical model lies in the fact that it may be used under extreme conditions which are too rare to be accurately and with sufficient statistical significance covered by empirical data. It should be noted that an extrapolation of an empirical model beyond the parameter range used to build it may render it invalid.

2.3. Developments in Thermospheric Data Assimilation

> *The ATMOP project will support European research activities on forecasting techniques by upgrading assimilation of thermospheric data into an existing semi-empirical model for near-real time prediction and developing thermospheric data assimilation based on a global physical thermosphere-ionosphere coupled model (CMAT2) .*

If space weather uses the definition employed in meteorology, a forecast is a type of prediction initiated from a state of the atmosphere at a unique time: this is distinct from a prediction based on mean climatology which would not distinguish the state tomorrow from that on the same date next year. This unique state is customarily represented by an analysis[4]. Nowcasting is a type of forecast that takes place when observations in the region of interest are dense and the forecast timescales are short, such that evolution of the atmosphere may be estimated with sufficient accuracy by first-order, linear processes represented by relatively simple models. Over longer timescales, the presence of chaos in meteorological systems progressively erodes the memory of the initial observations and forecast accuracy depends more heavily on the representation of non-linear processes as addressed by more complex physical models. In order to achieve more accurate forecasts of the thermosphere and ionosphere, it is therefore necessary to improve not just models of the thermosphere-ionosphere but also the assimilation techniques used to introduce observational data to them.

The uncertainty in operational orbit predictions (over a time span of 1-30 days, but in particular for the first few days) can be significantly reduced when the atmospheric density model is corrected for biases through near-real time assimilation of total density or drag data.

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[4] Here “analysis” refers to an estimate of the state of the atmosphere made using data assimilation of both observations and a model forecast

A data assimilation system relies on a plentiful supply of high quality, timely observations. Observations of the (neutral) thermosphere (e.g. air density), which one can utilize to improve estimates of thermospheric drag, are relatively scarce but can be obtained with low temporal and spatial resolution through processing of radar tracking data. This may explain why, to date relatively little work has been done on thermospheric data assimilation. Conversely, observations of the collocated ionized atmosphere (the ionosphere), chiefly from GNSS, are considerably more plentiful and therefore most efforts to date have concentrated on data assimilation for the ionosphere, not the thermosphere. Presently, only the US Air Force possesses a near-real time thermosphere prediction model, based on an empirical model. ESA currently uses MSIS (a US model) and therefore development of European capability begins to address a broad strategic need to reduce dependence of space operations on the US.

Although Europe has capability for physical modelling of the thermosphere (specifically, CMAT2) there are currently no operational services in place to provide regular, global ‘state of the atmosphere’ analyses for the thermosphere in an equivalent fashion to the provision of lower atmosphere data by meteorological services. Development of thermospheric data assimilation systems for such models is today a matter of fundamental research. We find it important to address these issues in the frame of the ATMOP project because it would pave the way towards the development of the operational systems for thermosphere nowcasts and forecasts that will rapidly become of primary importance.

In this project we propose two distinct yet complementary activities which will target thermospheric data assimilation.

A first strand of thermospheric data assimilation activity focuses on the semi-empirical model (DTM). DTM has the advantages of computational speed, simplicity of use, and portability, which are important criteria in view of ESA’s Space Situational Awareness programme. When used in situations similar to those for which they have been trained, empirical models are quite effective and compete favourably with more complex physical models over short forecast times. It is in particular the idea to assimilate CMAT2 output for selected cases (varying the solar flux, season, geomagnetic activity), as pseudo-observations, in DTM. This may possibly lead to a higher spatial resolution in the semi-empirical model, and it will certainly help constrain certain weakly-observed atmospheric variations. We will also use CMAT2 to investigate mechanisms which affect drag and to then see if those which we can identify can be parameterised. We have said above that gravity waves and small-scale dynamics cannot really be included in DTM, but simulation of tidal structures with CMAT2, for example, will show how tidal modes mix, and investigate the height propagation under different physical conditions. Insofar as these can then be related to the conditions under which DTM is run, and can be converted into simplified algorithms, the resultant variability can be included in the empirical model. By comparing different numerical model runs under differing dynamical regimes it will also be possible to relate the error bars to specific activity levels. In the context of major orbit modifications following a severe storm, the effectiveness of such models to produce a forecast which “allows for a mitigation of space weather effects” may be more limited.

The limitations of semi-empirical and empirical models are relevant to data assimilation and forecasting.

1. Such models often represent the climatological (mean) state, rather than the daily variations of it. Thus, analyses made at successive times use as their starting point a climatology rather than the atmospheric state at the previous analysis time. The period over which these models can produce forecasts of acceptable quality is quite short
2. Although empirical models are able to predict future behaviour of the thermosphere and ionosphere based upon their statistical understanding of similar past situations, they lack the ability of physical

models, which represent the basic Navier-Stokes dynamical equations, to evolve with accuracy atmospheric states not previously encountered.

3. These models tend not to represent any coupling between the ionosphere and thermosphere, thereby preventing knowledge of ionospheric conditions from improving predictions for the thermosphere. This is an important consideration, since currently ionospheric observations are more numerous than thermospheric observations, and a coupled analysis system thus has potential to exploit these ionospheric data to improve the representation of the thermosphere.

Over the longer term, therefore, it is expected that in order to address such drawbacks the next generation of operational systems will employ assimilation of both thermospheric and ionospheric data into global coupled thermosphere-ionosphere physical models. Developing capability for such systems represents a more profitable use of resources in the long term. Accordingly, a second strand of our thermospheric data assimilation work shall focus on building capability for a new data assimilation system based on a global coupled physical model (CMAT2). In the future, beyond the timespan of ATMOP, it is envisaged that reliable operational thermospheric modelling and forecasts will be achieved by such means.

The development of a thermosphere / ionosphere data assimilation system based on a physical model will take the lead from developments in meteorological data assimilation. The Met Office is a world-leader in this field and therefore is well positioned to apply this data assimilation knowledge to the development of a thermosphere / ionosphere data assimilation system.

Since the development of a physical model-based assimilation system is such a complex task, close assessment of the performance of the building blocks of this system is required throughout the project. As well as comparing results with independent data, it will be essential to compare results with those from DTM and from free forecasts (i.e. not initialized by assimilation) from CMAT2 in a range of test cases, ideally including present day solar minimum and historical storm conditions.

Benefits from the concurrent data assimilation activities arise because the greater simplicity of the semi-empirical model allows for more rapid development and testing of ideas. Effort which is expended on understanding, acquiring and processing thermosphere observations, including the derivation of observation operators and assessment of errors, will have direct application for development of thermospheric data assimilation into a global physical coupled model. Comparison of output from the two model systems allows the assessment of aspects such as the extent to which the use of ionospheric data impacts the evolution of the thermospheric forecast at different timescales, and production of an improved analysis state from the global system would allow experimentation to examine whether its use to initialise the semi-empirical model might improve predictions of the thermosphere in the near-real time.

3. PROGRESS BEYOND THE STATE-OF-THE-ART

3.1. Characterization of the thermosphere forcing

3.1.1. State of the art

The present characterization of thermospheric forcing in semi-empirical models involves solar and geomagnetic indices, most of which were defined several decades ago and are still used for continuity reasons. There is a strong need today to define new proxies that provide a better description of the external forcing while complying with the stringent requirements for operational services.

3.1.1.1. EUV forcing:

The thermosphere is mostly affected by the solar irradiance in the EUV (Extreme UltraViolet, 10-121 nm) band. This quantity cannot be measured from the ground, and no continuous measurements of the solar EUV spectrum were available until 2002. For that reason, most models today rely on the F10.7 index (i.e. the irradiance in the 10.7 cm wavelength) as a proxy for the EUV forcing. The variability of the F10.7 index indeed closely fits that of the EUV irradiance, and this proxy has been continuously measured on a daily basis since 1946, making it very convenient for long-term studies. The atmospheric absorption of the EUV, however, is strongly wavelength dependent, and so no single quantity can properly reproduce the EUV forcing at different wavelengths. Various new proxies have been introduced to correct for this. Best known is the Mg II index, which is appropriate for the MUV band (200-300 nm) but has also been advocated for thermospheric models.

Currently, thermospheric models such as DTM and JB2008 use the F10.7 index as a main solar input. The prime need today is for the definition of proxies 1) that properly reproduce the EUV forcing on time scales of days to decades, 2) that can be reconstructed in the past (for carrying out statistical studies), and 3) whose availability in the future is guaranteed. The key issue therefore is to define a set of robust proxies that properly describe the EUV forcing on the thermosphere while meeting the requirements of operational services.

3.1.1.2. Geomagnetic forcing:

Today operational thermosphere models use the 3-hour Kp (or equivalently 3-hour ap) planetary geomagnetic index to characterize the geomagnetic forcing of the thermosphere, whereas the preliminary CNES DTM model is based on the 3-hour am index. The complexity of the different processes that contribute to the perturbations of the thermosphere, meridional circulation enhancements, travelling atmospheric disturbances, and upwelling and downwelling of neutral gas constituents with respect to levels of constant pressure, result in a time lag between the variations of the electrodynamic drivers and the resulting change in the state of the neutral atmosphere. This time lag bears considerable uncertainty, and indeed, the values that are adopted in the construction of the models, vary. The DTM model uses a variable lag time from 3 hours at the pole to 6 hours at the equator. The Jacchia model series (including the first JB model) uses a constant value of 6.7 hours and the MSIS model series the full history over 57 hours of the 3-hour indices. The most recent model developed in the US, JB2008, uses the hourly Dst index in strong geomagnetic storm conditions.

Kp and am geomagnetic indices are planetary indices based on K indices measured at subauroral latitude observatories. An individual K index is an integer in the range 0 to 9 corresponding to a class that contains the largest range of geomagnetic disturbances in the two horizontal components during a 3-hour UT interval. The Kp network is composed of 13 observatories, 11 of them located in Western Europe and Northern America. The am index takes advantage of the better coverage in the wake of the International Geophysical Year (IGY) and the end of the cold war, and shows a strong improvement in the geographical distribution of the 20 observatories of the network. Dst measures the variations in the geomagnetic North component; based upon variations in the horizontal North component at four low latitude observatories, it aims to monitor the axi-symmetric part of the magnetosphere currents. It is mainly sensitive to the ring current and to the magnetopause Chapman-Ferraro currents.

It is now well established that the am planetary geomagnetic index is a better proxy than Kp when considering forcing of the thermosphere at mid to low latitudes along the orbit of CHAMP. It has also been shown that the lag times may be significantly shorter than those conventionally used to drive the models; in addition, they differ between day and night. Obviously there is a need today to define new proxies with a temporal resolution which is better than the established time, and with a spatial resolution which accounts at least for day/night differences. We therefore consider that there is also an important need to introduce physical arguments in addition to purely statistical and operational considerations in the choice of the geomagnetic proxies.

Solar and geomagnetic proxies are adequate for describing global-scale variations. Geomagnetic proxies are to some extent also applicable to regional scales (accounted for by geomagnetic longitude and latitude dependencies). In order to describe small-scale processes in magnetosphere-ionosphere coupling one has to either account for them as statistically modelled perturbations or through direct investigation of their effects on the state of the thermosphere. At present, a viable method to investigate small-scale ionospheric perturbations (due to turbulent mixing, plasma instabilities, field-aligned currents) and their energy dissipation into the thermosphere is a case study approach.

3.1.2. Progress

3.1.2.1. EUV forcing:

The description of the EUV forcing can be improved in two different ways. One is to use solar EUV spectra from existing (TIMED) or future (SDO) satellites as an input to upper atmospheric models. The longevity of such measurements, however, is not guaranteed. Furthermore, statistical studies have shown that the EUV forcing can be appropriately described by small (typically 2 to 6) set of variables, making high resolution spectral measurements superfluous.

Our strategy is to define a reduced set of solar proxies for the thermosphere out of existing solar indices (such as F10.7) or spectral measurements in specific bands (such as the H I Lyman-alpha line). The latter are today measured by radiometers (such as LYRA onboard PROBA2) whose longer lifetime over conventional spectrometers is a major asset for space monitoring. Two improvements will be made over existing approaches:

- A data-driven statistical approach will be used to seek the quantities that best describe the thermospheric density, rather than first imposing a set of proxies and then seeking their best combination. We pioneered this approach and applied it so far to the reconstruction of the solar EUV spectrum from the measurement of a few spectral lines. This statistical study first requires the creation of a database of harmonised densities (deliverable 2.1).

- A multiscale approach will be used to decompose each quantity into different time-scales, each of which can then be tuned separately. Another possibility would be to use a linear time-invariant parametric model. We recently found that the nowcast error of the thermospheric density can be reduced that way by 10 to 40%.

The next step is the forecast of the EUV flux (and hence thermospheric density changes) with a horizon of a few days. The transition from nowcast to forecast requires a completely different strategy, in which solar images in the EUV (taken from SDO and SOHO) need to be used. Indeed, by comparing the flux emitted by the western and eastern limbs, the evolution of the spectral variability can be anticipated a few days ahead. This idea has been advocated by several authors but has not yet been implemented.

3.1.2.2. Geomagnetic forcing:

Both geomagnetic indices, Kp and am, do not take advantage of the present routine online availability of digital values for most of the observatories. At the latitudes where am observatories are located, the range on which a K index is based is a statistical proxy of the magnetic energy related to the geomagnetic activity during the corresponding 3-hour interval. Because of the morphology of the transient geomagnetic variations, this is no longer the case for time intervals significantly different from three hours. The availability of digital values makes it possible to consider other proxies of the energy, such as the root mean square, that remains physically meaningful whatever may be the duration of the time interval over which it is computed. We will consider using rms-based geomagnetic indices with a time resolution down to 30 minutes.

One of the objectives of the project is to find the best possible granularity for estimating this quantity. Another objective of the project will be to assess whether or not it is of interest to use regional geomagnetic activity indices rather than planetary ones. Because of the Poynting theorem, the rms of the irregular variations in the horizontal components of the magnetic field is proportional to the magnetic energy related to the geomagnetic activity. At the locations of the am observatories and for 3-hour intervals, the morphological features of the geomagnetic activity are such that the range is statistically proportional to the rms, with a 30-50 % dispersion. Using the rms as proxy for the energy will significantly improve the precision in the magnetic energy monitoring. It will also allow a better determination of the lag times to be used in the models.

We will also consider using other geomagnetic indices such as for example the Dst index already used in JB2008 (or the SYM/ASY indices available as minute values) and the Polar Cap (PC) magnetic index that aims at monitoring the magnitude of the transpolar part of the polar ionosphere current system. PC is linearly correlated in a statistically optimal way with the solar wind merging electric field. PC has been used in several studies as an indicator of the integrated Joule heating rate which is the prevalent contributor to auroral energy deposition in the thermosphere.

Proxy assessment will be based on statistical analyses of the total densities inferred from the accelerometer measurements made onboard the CHAMP and GRACE satellites. The statistical analysis will render useful results mainly for low up to medium geomagnetic activity. In addition and more specifically for larger activity levels when the statistics are poor (i.e. typically for Kp larger than 6) we shall use physics based arguments. Event studies will be performed on space weather events where a substantial amount of space borne and ground based observations exists, and runs of physical models, presently available in Europe and in North America, will be conducted in support of the studies. The final choice of proxies to be used in the development of the new DTM model will also be based on operational arguments, as our final task is to provide the proxies on-line and in near real-time.

The next step is the forecast of the geomagnetic proxies with a horizon of a few days. The transition from nowcast to forecast requires a completely different strategy, in which in situ measurements of the solar wind parameters at L1 need to be used. We will use methods that have already demonstrated their efficiency in this domain, such as, e.g. neural networks.

The characterization of geomagnetic forcing will be pursued beyond the choice of proxies to be used in the new DTM model. Indeed, we want to better understand in terms of physics the connection between external drivers observed at their origin (in the solar corona and in the solar wind) and the effects on the thermosphere in order to prepare the next generation of thermosphere models.

3.2. Development of a new DTM semi-empirical model

3.2.1. State of the art

Semi-empirical models of the upper atmosphere are presently used in orbit determination and also in orbit prediction of satellites as well as debris in Low Earth Orbit (LEO) or with a perigee approximately below 1000 km altitude. These models predict instantaneous density as a function of the location (altitude, latitude, longitude, local time), solar and geomagnetic activities, and date.

State of the art of semi empirical models is currently at the 10-15% level for altitudes below about 500 km, and 15-20% for altitudes in the range 500 to 1000 km (1σ uncertainties). However, these best performances are not achieved with a single model: JB2008 is most accurate for altitudes below 500 km but has a large bias of 30-40% for higher altitudes, whereas DTM and MSIS achieve a description of equivalent quality below and above 500 km with an uncertainty of about 15-20%. It is worth noting here that most LEO spacecraft are in the 500-900 kilometres altitude range, and thus do not take advantage of the good JB2008 performances.

Currently, of all force models present in a satellite orbit determination program, the drag computation is the least accurate. When tracking data on a satellite are available (GPS, DORIS, Satellite Laser Ranging; Two-line elements to a lesser degree), the density model errors can be minimized through the estimation of density scale factors. For precision orbit determination purposes, scale factors are estimated a few times per day up to every 10 minutes approximately. However, when tracking data are absent, as in the case of orbit prediction computations, satellite positions and velocities are propagated with the imperfect force model. This results in erroneous orbit predictions, which may result in temporary loss of contact with ground stations, imperfect manoeuvre planning, or in the worst case in collisions due to not executing a collision-avoidance manoeuvre.

The solution to this problem lies in improved estimates of upper atmosphere density, for which one first needs a good quality global representation of the thermosphere. The objective is to improve the semi-empirical DTM model in the 250-1000 km altitude range of the upper atmosphere thanks to the use of more representative solar and geomagnetic activity proxy indices, as well as by assimilating more total density data that are representative of nearly all conditions.

3.2.2. Progress

The error in orbit determination and the uncertainty in orbit predictions and lifetime estimates (other error sources however, solar cycle forecast in particular and mean surface-to-mass ratio of an inactive satellite, are more important) can be significantly diminished when the atmospheric density model is the least biased possible. This model will also be the background model in the near-real time data assimilation process. Therefore it has to be as accurate as possible in view of data gaps in the near-real time data stream.

A first objective is to improve the DTM model to at least the performance of JB2008 at low altitudes, while maintaining or improving performance for higher altitudes too. Although the drag effect is less at higher altitudes it is in fact a very important issue to achieve the best possible modelling at these altitudes since they contain a large number of Earth observation satellites.

The use of data covering several solar cycles including the present extreme low in combination with optimum indices will enable the construction of a least-biased model, which is the most important criterion in orbit computation and lifetime estimates in particular. The database will include densities inferred from CHAMP and GRACE accelerometers, which supplied high quality thermospheric density data over almost one solar cycle, including years of high geomagnetic activity such as 2003, and years of exceptional low solar activity such as 2008 and 2009. Additional densities at about 255 km will be inferred from GOCE accelerometer and ion thruster data. Total densities will also be derived from the analysis of GPS data on the DEIMOS-1 and PROBA2 satellites. The database will also include daily mean densities obtained through orbit analysis of Starlette and Stella. Mean densities will also be derived using radar tracking data (two-line elements: TLE) in a procedure similar to that of the US Air Force Space Command. Note that CNES already maintains the most complete and up to date density database in Europe thanks to its involvement in the CHAMP mission (CNES provided the accelerometer and is responsible for in-orbit calibration and validation).

The geomagnetic activity model will be significantly enhanced thanks to indices that are more representative of the perturbation and which have a higher temporal resolution too of 30 minutes instead of 3 hours. This will give the model a significant advantage in timing of storm onset over present models that are limited by the 3-hourly geomagnetic index. The analysis of case study results of a high-resolution physical model will allow a better understanding of the three-dimensional density variations during a geomagnetic storm or a solar flare for example. This information, which is provided through WP3, will be used to increase the fidelity of the modelling algorithm. This kind of constraint via a physical model is vital to the improvement of the semi-empirical model because the available density data never provide a complete view of an atmospheric event due to satellite sampling issues. The concurrent development of physical and semi-empirical models, which will be beneficial to both, is a premiere of this project.

The new DTM model, downloadable from a dedicated website (WP6), will present significantly reduced biases (systematic errors) and uncertainty as a function of altitude, local time, season, and solar (EUV and geomagnetic) activity, data allowing, which for the best models presently are 12-15% and 15-20% for 250-500 and 500-1000 km altitude, respectively, in order to reduce the error in satellite orbit determination and lifetime estimates.

3.3. Data assimilation for global analysis and near-real time prediction

3.3.1. State of the art

To date, only a limited amount of work has been done to assimilate total density or other neutral atmosphere (thermosphere) data into near real time drag models – this work has either been done in the US, or in Europe (Delft, ESOC) using an American semi-empirical model. By contrast, there has been more activity in the field of ionospheric data assimilation. Ionospheric analyses and forecasts are often carried out using empirical models which have a limited predictive capability. In the US, attempts have been made to produce ionospheric analyses and forecasts using global physical models, with to date moderate results, and no equivalent work has been attempted in Europe. Such work focuses chiefly on the ionospheric state, and any impact on the thermosphere (via model coupling) has not yet been examined. Although a number of ionospheric assimilation models (without thermosphere) have been developed, a fully coupled ionosphere / thermosphere assimilation and modelling system has not yet emerged. Constraining such a global physical model with assimilated thermospheric and ionospheric data will advance the state of the art in this area and build capability for future scientific developments beyond the duration of the proposed project.

3.3.2. Progress

Within ATMOP, research in the following areas can push scientific knowledge beyond the state of the art:

- Enhanced processing and understanding of total density data such that they are suitable to be used in data assimilation (e.g., characterization of observation errors, observation operators, etc)
- Assimilation of total density data in a near real time semi-empirical thermospheric density model, using the most accurate climatological model as background, with the aim of producing improved drag estimates
- Development of an ionospheric / thermospheric analysis and forecast system based on a physical general circulation model. This will be a first in Europe (only done in US to date).
- Use of model ionosphere / thermosphere coupling to investigate the impact on the thermosphere of the assimilation of ionospheric observations. This will be a global first, and validation of results using independent total density data shall also be innovative.
- Via work on total density assimilation and development of physical model-based data assimilation, building capability for future system in which fully coupled ionospheric / thermospheric analysis and modelling is possible. This will be groundbreaking.

As this part of the project requires fundamental research in a field that is relatively unexplored, it is impossible to give fair and reliable quantitative estimates of the improvement in the global thermosphere description. The development costs of meteorological data assimilation are very high. As an example, the Met Office spent approximately 42 person years on the development of its 3 dimensional variational (3D-Var) assimilation system. This shows the non-trivial nature of developing a data assimilation system. On this basis, the risk of not being able to significantly build capability for a physical model-based thermosphere / ionosphere data assimilation system within the duration of ATMOP appears high. However, this risk is mitigated by the following factors:

- Exploiting the outcomes from 3D-Var and subsequent assimilation research at the Met Office ensures more rapid progress (possibly up to an order of magnitude quicker).
- Some aspects of data assimilation system design may become less resource-consuming the higher one goes in the atmosphere (for example, significantly fewer observation types to simplify the process, fewer assimilation analysis variables, compared to meteorological data assimilation).

- The meteorological 3D-Var development included extensive activity to trial and validate results to ensure that 3D-Var worked robustly as an operational system and produced better quality analyses and forecasts than the assimilation system it was designed to replace. This activity is unnecessary within ATMOP since the assimilation system under development is pre-operational.

3.4. Summary

Table 4 summarizes the ATMOP activities in terms of:

- "baseline" (i.e. "where does the project work start");
- “baseline data” (i.e. the data against which the project will measure its progress);
- results that the project aims to achieve,
- "performance/ research indicators" (i.e. criteria along which results, progress and impact of the project will be measured in later reviews and assessments).

Table 4: ATMOP Progress beyond the state of the art: a summary

	Baseline	Baseline data	Expected ATMOP achievements	Performance/research indicators
EUV forcing	Current parameterization in semi-empirical models	“Classical” (F10.7, MgII indices), and Solar 2000 proxies.	Reduced (2 to 6) set of proxies describing the EUV solar spectrum	Statistical comparison (using ATMOP density database) between observations and results of modelling using “classical” or ATMOP proxies
Geomagnetic forcing	Current parameterization in semi-empirical models	“Classical” proxies: Kp/ap and/or Dst, … geomagnetic indices	New proxies with better time and/or longitude resolution.	
New DTM semi-emp. Model	Current DTM version, and currently used semi-empirical model	Current results of thermosphere density semi-emp. modelling.	New DTM_2012 semi-empirical model	Statistical comparison between observed and modelled densities
Physical modelling of the atmospohere-	Current CMAT2 global model	Current model results of the coupled thermosphere-ionosphere	Improved thermosphere modelling under particular/complicated conditions	Model score with data assimilation included

	Baseline	**Baseline data**	**Expected ATMOP achievements**	**Performance/research indicators**
ionosphere		system	based on physical understanding	
Thermosphere data assimilation	Atmospheric density models (no near-real time models in Europe)	Densities inferred from satellite orbits and sensors	Model with near-re al time capabilities	Model score versus reference climatology models and versus persistence

4. WORK PACKAGE DESCRIPTION

4.1. WP1: Project Management

Work package number	1	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Project Management**				
Activity type	MGT				

Objectives

This work package is devoted to the project management. It includes: operational, financial, technical, legal and knowledge management and ethical, society and gender issues during the project lifetime.

Description of work

A Periodic Activity Report will be delivered on months 12, 24, and 36 covering the content foreseen in the contractual “Periodic activity report” as well as effort and expenditure. The main activities involved in this work packages are the following:

Task 1.1 Day to Day work management.

Month1-Month36 (Partners: DMS/All)

It includes control of partners‘ activities and deliverables status, logistic organization of meetings (internal and review) and audio/video conferences, acting as front end with the EC and updating other partners about the project evolution, ensuring the adoption of the quality plan, managing actions against partners in default, conflict resolution, reporting the EC services and contacting them for administrative purposes, coordinating the periodic activity report on months 12, 24, and 36, Coordinating quarterly periodic activity reports every three months, Coordination of the final report, and submission of amendments if needed.

Additionally, contacts with external entities operating satellites will be made when appropriate, in order to facilitate Task 6.2 devoted to contact possible users of our products.

Task 1.2 Administrative and Financial Management

Month1-Month36 (Partners: DMS /All)

It includes: collection and submission of all the cost incurred by the partners during the period, managing and monitoring overall budget, obtaining certificates on financial statements whenever they are needed, transferring sums to the partners after the payment by the EC according to the terms of the consortium agreement and financial schedule.

Task 1.3 Quality and risk management

Month1-Month36 (Partners: DMS)

It includes activities for preparing the quality and risk management plan and monitor the project in this regard.

Work package number	1	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Project Management**				
Activity type	MGT				

Task 1.4 Legal and Knowledge Management

Month1-Month36 (Partners: DMS/all)

It includes negotiation and monitoring the consortium agreement and the Intellectual Property Rights. It includes the identification of ways of protecting project results, if deemed necessary, including patents, open-source licensing and trademarks.

This task will start with an internal IPR audit conducted by the consortium members themselves to identify results with exploitation potential and impact. Details of IPR related concerns will be laid out in the Consortium Agreement.

Task 1.5 Ethical, Society and Gender issues.

Month1-Month36 (Partners: DMS)

We will also monitor the social and gender issues encountered during the ATMOP project life.

Deliverables

Months 3, 6, 9, 15, 18, 21, 27, 30, 33:	D1.1 Quarterly report (by all, Report/Restricted)
Month 12:	D1.2 Quality and Risk Contingency Plan (by DMS, Report/Restricted)
Months 12, 24:	D1.3 Periodic Activity Report (by all, Report/Restricted)
Month 36:	D1.4 Final Report (by all, Report/Restricted)

4.2. WP2: Forcing the thermosphere: physical processes and proxies for semi-empirical modelling

Work package number	2	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Forcing the thermosphere: physical processes and proxies for semi-empirical modelling**				
Activity type	RTD				

Objectives

Main objectives of this Work package are:

- ☐ to identify the best possible EUV and geomagnetic proxies for describing the solar and geomagnetic forcing of the thermosphere in Space Weather models;
- ☐ to set up tools enabling timely on-line delivery and nowcast of the proxies to be used in the pre-operational Drag Temperature Model (DTM) of the thermosphere developed in WP 4;
- ☐ to develop a prototype forecast of EUV forcing up to several days ahead;
- ☐ to develop a prototype forecast of the geomagnetic proxies based on solar wind data at L1;
- ☐ to understand the influence and relative importance of various physical processes in the solar wind- magnetosphere-ionosphere system on the behaviour of the semi-empirical model.

Description of work

Task 2.1 - Database construction for proxies assessment

Month 1 –Month 3 (Partner: CNES)

We will establish a selection of existing thermosphere total density data sets that are the most appropriate for tasks 2.2 and 2.4. Due to the entirely different heating mechanisms, the temporal and spatial resolutions required for those tasks are not the same. Study of the upper atmosphere heating due to solar EUV emissions requires global mean densities with a temporal resolution of typically one day, whereas the study of heating due to geomagnetic perturbations necessitates data with a time resolution of the order of an hour and a spatial resolution of few tens of km. Daily mean densities obtained from satellite orbit analysis are adequate for the former study and densities inferred from accelerometer data are most relevant to the latter. Data processing effort is required to convert sparsely and unevenly sampled density measurements into data sets that can be efficiently processed in tasks 2.2 and 2.4.

Task 2.2 - EUV forcing and solar proxies

Month 4 –Month 35 (Partner: CNRS)

We will assess the EUV forcing on the upper atmosphere and determine a proper set of spectral bands or solar proxies that can be used as inputs for operational models. The first step is the delivery of a nowcast of the solar EUV spectrum from on-line open access satellite data and solar proxies, in collaboration with WP6. This step will largely be based on the experience the contributors have gained from the FP7 SOTERIA project. The second and much more challenging step is to prepare the delivery of solar EUV forecasts (on time scales of hours to days and with a granularity of a few hours), since this requires in addition the analysis of solar EUV images, a good understanding of the underlying physical processes and the development of an empirical prediction model. The main contributor of this second step will be a PhD student to be hired by the project

Work package number	2	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Forcing the thermosphere:** **physical processes and proxies for semi-empirical modelling**				
Activity type	RTD				

Objectives

Main objectives of this Work package are:

- ☐ to identify the best possible EUV and geomagnetic proxies for describing the solar and geomagnetic forcing of the thermosphere in Space Weather models;
- ☐ to set up tools enabling timely on-line delivery and nowcast of the proxies to be used in the pre-operational Drag Temperature Model (DTM) of the thermosphere developed in WP 4;
- ☐ to develop a prototype forecast of EUV forcing up to several days ahead;
- ☐ to develop a prototype forecast of the geomagnetic proxies based on solar wind data at L1;
- ☐ to understand the influence and relative importance of various physical processes in the solar wind- magnetosphere-ionosphere system on the behaviour of the semi-empirical model.

Task 2.3 - Physics of electrodynamic forcing

Month 1 –Month 30 (Partner: CNRS)

We will go through several steps in order to understand the physics involved in the coupling between solar and geomagnetic activity and thermospheric variability. The goal is to better understand in terms of physics the connection between external drivers observed at their origin (in the solar corona and solar wind) and the resultant response of the thermosphere. The results will have significant bearing upon the refinement of the semi-empirical model developed in the framework of the ATMOP project, and will help to clarify why the empirically selected proxies work best and which physical conditions limit their application. The task comprises the following elements:

- ☐ perform studies of the response of the thermosphere to space weather events for cases where a substantial amount of space borne and ground-based observations exist
- ☐ run existing physical and semi-empirical models presently available in Europe and North America on these events
- ☐ investigate the role of intense small-scale magnetosphere-ionospheric coupling processes on geomagnetic activity and thermospheric variability
- ☐ investigate the physical effects of such changes of the magnetosphere-ionosphere system on the thermosphere which are non-uniform in space and time.

Task 2.4 - Geomagnetic proxies

Month 4 –Month 35 (Partner: CNRS)

We will identify new geomagnetic activity proxies for describing the neutral atmosphere response to the interaction between the interplanetary medium and the Earth environment. The first step will be to list and assess the indices used in presently available models and any other available geomagnetic proxies and to define a method for proxy assessment, considering the density database built in task 2.1.

The second step will be to determine the most appropriate proxies and their time and space resolution according to physically based criteria (in connection with task 2.3) and operational constraints. We will also prepare the numerical proxy database for DTM and make available on-line the geomagnetic proxies within one hour or less, through the ISGI portal (hosted by LATMOS), in collaboration with

Work package number	2	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Forcing the thermosphere:** **physical processes and proxies for semi-empirical modelling**				
Activity type	RTD				

Objectives

Main objectives of this Work package are:

- ❑ to identify the best possible EUV and geomagnetic proxies for describing the solar and geomagnetic forcing of the thermosphere in Space Weather models;
- ❑ to set up tools enabling timely on-line delivery and nowcast of the proxies to be used in the pre-operational Drag Temperature Model (DTM) of the thermosphere developed in WP 4;
- ❑ to develop a prototype forecast of EUV forcing up to several days ahead;
- ❑ to develop a prototype forecast of the geomagnetic proxies based on solar wind data at L1;
- ❑ to understand the influence and relative importance of various physical processes in the solar wind- magnetosphere-ionosphere system on the behaviour of the semi-empirical model.

WP6 Task 6.1.

The final step is to develop a prototype forecast of the DTM geomagnetic proxies using in-situ measurements of the solar wind parameters at L1. For this step, a post-doc is to be hired by the project.

Deliverables

Month 3:	D2.1 Fully documented harmonized database of thermospheric densities (by CNES, restricted)
Month 12:	D2.2 Report on recommendations for the most appropriate solar EUV bands and proxies to be used as inputs for the DTM model and numerical database of the solar proxy (by CNRS, restricted)
Month 18:	D2.3 Nowcast of the solar EUV spectrum for upper atmospheric specification and proxies to be used in DTM. (by CNRS, public)
Month 24:	D2.4 Report on recommendations about the most relevant geomagnetic proxies to be used as inputs for the DTM model and numerical database of the geomagnetic proxies (by CNRS, restricted)
Month 30:	D2.5 Nowcast of the geomagnetic proxies to be used in DTM (by CNRS, public)

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- ☐ to understand the influence and relative importance of various physical processes in the solar wind- magnetosphere-ionosphere system on the behaviour of the semi-empirical model.

Month 35:	D2.6 Report on the physical investigations on electrodynamic forcing (by CNRS, public) D2.7 Prototype forecast of the solar EUV spectrum (by CNRS, public) D2.8 Prototype forecast of the DTM geomagnetic proxies (by CNRS, public)

4.3. WP3: Modelling of Thermospheric Drag Processes

Work package number	3	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Modelling of Thermospheric Drag Processes**				
Activity type	RTD				

Objectives

The concept and objectives of this workpackage are:

- ☐ To assist development of the semi-empirical thermospheric density model DTM by evaluating possible improvements and changes using a physical model of the coupled thermosphere-ionosphere system
- ☐ To build capability for ionosphere / thermosphere data assimilation based on a global physical model, which shall ultimately be the successor to semi-empirical methods

A numerical model of the Earth’s thermosphere and ionosphere has been in development at UCL since 1981. This has led to a range of models culminating in CMAT2 (Coupled Middle Atmosphere and Thermosphere model) which draws on the expertise gained from the more well-known CTIP (Coupled Thermosphere Ionosphere and Plasmasphere) model but which takes its lower boundary down to 15km altitude. CMAT2 works by solving the Navier Stokes equations of energy, momentum and composition on a latitude, longitude, pressure level grid. It has variable resolution but is most often used with either 2 degrees latitude, 18 degrees longitude, 1/3 scale height grid or 5 x 5 x 1/3 scale height.

It is most useful looking at the effects of varying the controlling inputs rather than for producing absolute parameter values – that is, it is a tool for looking at the physics of processes in the atmosphere rather than a model of absolute values. We propose to use this in a number of ways to aid the development of the semi-empirical model that is the main subject of this collaboration.

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Description of work

Task 3.1 - Evaluate best subset of CMAT2 to use for the tests

Month 1 – Month 3 (Partner: UCL/CNES)

CMAT2 is a global 3-d coupled ionosphere-thermosphere model which has a lower boundary at 15km and which includes a number of processes which may not affect thermospheric density. CMAT2 is very flexible in the way it can be configured, and so it can be tailored to specific tasks. In this first part of the project we will evaluate the best subset of the program to use for the study. For example it is probably unnecessary to use the full altitude range: gravity wave parametrizations may be unnecessary. We will consult with the providers of the semi-empirical model to see what range of input parameters

Work package number	3	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Modelling of Thermospheric Drag Processes**				
Activity type	RTD				

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and dependencies are included in DTM to inform this decision.

Task 3.2 - Initial model runs

Month 4 –Month 25 (Partner: UCL/CNES/CNRS/CLS)

This project is mainly aimed at finding improvements to the DTM. The role of the physical modelling in this will be to evaluate the physical basis on which improvements to the semi-empirical model are suggested. An example might be to modify an algorithm in the program which expresses a relation between the input parameters and the produced output. The physical model can be used to examine the correlation between the inputs and outputs of the algorithm (and understand the physical basis of them) to see if the suggestion is physically well-based. It is difficult to say how much time this will use as it depends on how many changes are suggested and how complex they are. We assume one major (three month) study every 6 months.

As part of this task we will also evaluate the use of the current semi-empirical model as an input to CMAT2 and whether that improves the absolute values in the model output. This will be done by

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Work package title	**Modelling of Thermospheric Drag Processes**				
Activity type	RTD				

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running some test runs of CMAT2 ab initio and comparing to runs using the semi-empirical model as starting point. This latter will require a small amount of development of CMAT2.

Another important element at this stage will be to look at the suggested control variables that would be used for putative assimilation tests for the thermosphere part of the model. This will require some consultation with the MetOffice who will be leading the assimilation work. The Met Office already have a version of CMAT2 which they will be gaining experience with but we expect at least a person month of UCL time will be needed to run initial tests at this stage.

Task 3.3 - Runs to evaluate use of different input proxies

Month 6 –Month 25 (Partner: UCL/CNES/CLS/CNRS)

This will look at first how the EUV fluxes control the thermospheric energetics and dynamics, and then would look at the proxies to see how well they express that control. Any suggested modifications to the proxies or the way they are introduced will be tried out in the physical model, to ascertain whether they should improve the semi-empirical description. The manpower requirement assumes three short

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Work package title	**Modelling of Thermospheric Drag Processes**				
Activity type	RTD				

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studies.

Task 3.4 - Comparisons with data

Month 1 –Month 30 (Partner: UCL/CNES/CNRS)

Some work will be carried out early in the project to compare the current model output to data. Initially data used will be the two-line elements (TLEs) available from general satellite tracking data: this is fairly low resolution. After about six months data from CHAMP (300 km) and GRACE (400 km) at high resolution (every 80/160 km along the orbit respectively), plus several other satellites can be compared. These initial tests will enable the absolute densities and temperatures in the model to be tuned to the right average values and thus enable a comparison between the variability in the numerical model and the data. These should be fairly close but it is possible some remedial work will be needed at this stage. This is an important precursor stage to getting the later assimilation incorporated into CMAT2. Satellite data is scarcer below 300 km and JB model data will be used for the comparisons between 200 km and 300 km.

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This task will also look at whether it was possible to improve the now- and fore-casting capabilities of the semi-empirical model by using numerical routines to do some pre-manipulation of parameters or algorithmic dependencies before DTM does its main calculations. (For example, can measurements of the O/N_2 ratio be used to improve the Ne forecasts and hence feedback from there to thermospheric densities and temperatures). This is highly speculative at this stage and only a small part of the UCL effort has been allocated to it. If this is not used the time will be used in the other parts of this task or Tasks 3.2 and 3.3

Task 3.5 - Evaluation of data assimilation by testing in numerical models

Month 1 –Month 33 (Partners: UCL/CNES/MET/*CNRS)*

In their own work package the Met Office will have been looking at incorporating data assimilation techniques into both ionospheric and thermospheric elements of the model(s). We are concerned here primarily with incorporating data assimilation techniques into the thermospheric component and in particular whether drag estimates from satellite/debris tracking systems or other data sources can be

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Activity type	RTD				

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used. Our collaborators on CTIP in NCAR/NOAA in Boulder, Colorado, already have expertise in introducing satellite data into the thermospheric component of the model. We do not need to reproduce this (we can report on it –results were disappointing due to the small amount of data available) but we can use their experience to inform how we try to incorporate re-entry drag data. We will also of course heavily rely on consultation with the Met Office – we have not included costing for this in our WP on the assumption that is already catered for in WP5.

The work that has been done on improving the ionospheric models will need to be evaluated in terms of seeing how important a component the ionospheric input is to the thermospheric densities (our ultimate goal!) so tests will be carried out to evaluate the quantitative effect variations in the ionosphere will have on the thermospheric density and velocity structure. This will be done early in the project. At around 15 months in we shall also do tests to determine how long the model takes to return to "equilibrium" after a range of parameters is "forced" away fro the free-running self-consistent state. This is important to judge the likely response times and stability when data is assimilated in later.

Towards the end of the project we will then try to incorporate data assimilation techniques into the

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physical model.

The majority of the work in the task will be to evaluate how assimilation of the drag data might be used in the numerical model to improve short-term forecasts: ie can this information be used to improve the semi-empirical models? We will evaluate this by incorporating the drag data into CMAT2 and looking at the physical consequences of "forcing" this towards the measured morphology. A series of integrating and trialling tests will be carried out over the period 28-34 months into the project and this will be done in close association with the MetOffice (who will also have their own version of the model). While the main goal will be improving the empirical model, a secondary goal will be improvement in the physical model itself and evaluation of assimilation of data into this ands its potential for the future.

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Deliverables

Month 4:	D3.1 Report on the evaluation of the best subset of CMAT2 to be used for the tests (by UCL, restricted)
Months 7, 13, 19, and 24:	D3.2 Reports on physical interpretations (by UCL, restricted)
Month 12:	D3.3 Report on runs to evaluate use of different input proxies (by UCL, restricted)

Work package number	3	**Start date:**	T0	**End date:**	T0+36 months
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Month 9, 21, and 33:	D3.4 Reports on comparison with data (by UCL, restricted)
Month 9, 21, and 33	D3.5 Reports on evaluation of data assimilation (by UCL, restricted)

4.4. WP4: Semi-empirical modelling of the thermosphere

Work package number	4	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Semi-empirical modelling of the Thermosphere**				
Activity type	RTD				

Objectives

The objective of WP4 is to improve the semi-empirical DTM model in the 250-1000 km altitude range of the upper atmosphere by means of more representative solar and geomagnetic activity proxy indices, as well as by assimilating more total density data. It is not possible to improve the model for lower or higher altitudes than the above-specified range due to the absence of data, but drag becomes a minor to negligible problem above 1000 km anyway.

The new DTM model, downloadable from a dedicated website (developed in the framework of Task 6.1), should present significantly reduced biases (systematic errors) and uncertainty as a function of altitude, local time, season and solar activity, data allowing, which for the best models presently are 12-15% and 15-20% for 250-500 and 500-1000 km altitude, respectively, in order to reduce the error in satellite orbit determination, operational orbit prediction (with impact on the reduction of risk due to possible collisions), and satellite lifetime estimations in particular.

Description of work

Semi-empirical models of the upper atmosphere are presently used in orbit determination and also the orbit prediction of satellites as well as debris in Low Earth Orbit (LEO) or with a perigee approximately below 1000 km altitude. The error in orbit determination and the uncertainty in orbit predictions and lifetime estimates can be significantly diminished when the atmospheric density model is the least biased possible. This kind of model improvement can only be achieved by simultaneously addressing the issues of the spatial and temporal resolution of the density data and the solar and geomagnetic activity indices used in the modelling. The former point is the topic of Task 4.1 and Task 2.1, which consist of producing a complete density data set covering the required altitude range for at least a solar cycle. The complete coverage of the density data set is essential to the semi-empirical model, which has to be constrained by observations, or physical results (WP3) under all conditions. WP2 will determine and provide the optimum set of solar and geomagnetic indices for the DTM model. The model algorithm must be modified in order to achieve the highest possible gain of the new indices as well as to accommodate outcomes of specific results of WP3.

Assimilation of all density data with the new indices and the improved modelling algorithm will result in the least-biased *mean* (i.e., a stationary thermosphere without inter-annual variations) DTM model (Task 4.2). The model accuracy will be quantified through comparison of orbit computation results obtained with reference models and the new DTM (Tasks 4.3 and 4.4).

Task 4.1 Creation of the density data base

Month 1-Month 12 (Partners: DMS/CNES)

Task 4.1 consists of deriving the additional thermosphere total density data that will be assimilated in DTM. Densities inferred from CHAMP and GRACE accelerometer data and daily mean densities obtained through orbit analysis of Starlette and Stella are available through WP 2.1. Additional densities at about 255 km will be derived (or directly provided by ESA) using GOCE accelerometer

Work package number	4	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Semi-empirical modelling of the Thermosphere**				
Activity type	RTD				

Objectives

The objective of WP4 is to improve the semi-empirical DTM model in the 250-1000 km altitude range of the upper atmosphere by means of more representative solar and geomagnetic activity proxy indices, as well as by assimilating more total density data. It is not possible to improve the model for lower or higher altitudes than the above-specified range due to the absence of data, but drag becomes a minor to negligible problem above 1000 km anyway.

The new DTM model, downloadable from a dedicated website (developed in the framework of Task 6.1), should present significantly reduced biases (systematic errors) and uncertainty as a function of altitude, local time, season and solar activity, data allowing, which for the best models presently are 12-15% and 15-20% for 250-500 and 500-1000 km altitude, respectively, in order to reduce the error in satellite orbit determination, operational orbit prediction (with impact on the reduction of risk due to possible collisions), and satellite lifetime estimations in particular.

and ion thruster data. Total densities can also be derived analysing GPS data on satellite DEIMOS-1.

Mean densities can also be derived using radar tracking data (two-line elements: TLE), which is available for a very large number of objects (both active and inactive satellites as well as debris). In this task, a selection of TLE-tracked spacecraft will be used based on their altitude, local time and knowledge of their properties in order to complement the above-listed available density data sets. For such a purpose, the following activities will be carried out:

- ☐ Select the most appropriate non-active spacecraft for the TLE data processing, taking altitude and local time coverage into account.
- ☐ Adapt and optimize orbit determination software for the TLE processing and subsequent density derivation.
- ☐ Evaluate the accuracy of the TLE-densities.
- ☐ Document the TLE-densities database.

Task 4.2 Revision and upgrading of the DTM model

Month 13-Month 29 (Partners: DMS/CNES/CLS)

The DTM model will be revised using new solar (at stage 1) and geomagnetic activity (at stage 2) indices (Tasks 2.2 and 2.4 output, respectively), assimilating all total density data available in the CNES database as well as the densities produced in the framework of Task 2.1 and Task 4.1. This database is presently the most complete and up-to-date, containing in particular all densities inferred from accelerometer data, as well as most historical mass spectrometer and temperature data. Some density data sets require preprocessing, such as calibration, filtering and outlier rejection, prior to the model re-computation. The model algorithm requires modifications in order to be compatible with the new indices, due to the inclusion of WP3 case study results, as well as for a better portability.

Activities at Stage 1 include:

- ☐ Preprocessing of the density data sets (calibration, filtering, smoothing, data screening).
- ☐ Modify and optimize the DTM algorithm.

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- ☐ Normal equation computation, optimal weighting, and model coefficient estimation using the new solar activity indices.
- ☐ Internal quality evaluation, i.e., the formal precision.
- ☐ Develop DTM_2011 model package (install information, benchmark, and model documentation).

Activities at Stage 2 include:

- ☐ Normal equation computation and model coefficient estimation using the new geomagnetic activity indices.
- ☐ Internal quality evaluation, i.e., the formal precision.
- ☐ Update DTM model package for DTM_2012.

DTM_2011 and DTM_2012 will be the basis for the DTM_nrt development in WP5.

Task 4.3 Validation of the model parameters

Month 19-Month 30 (Partner: CLS)

Task 4.3 consists in analyzing the response of the physical parameters in the new density models (DTM_2011 and DTM_2012) to the solar and geomagnetic conditions. Among the physical parameters, the thermospheric temperature is an important one. The validation will be applied to vertical profiles but also to spatial and temporal variability (seasonal and solar activity response for example). Quiet but also stormy solar and geomagnetic conditions will be considered. The new indices for the solar and the geomagnetic activities that will be generated in the framework of WP2 will be used as inputs for the validation. The results of this validation are described in the documentation contained in the DTM model packages (see deliverables list).

Task 4.4 Validation of the density models through orbit computations

Month 19-Month 30 (Partners: DMS/CLS)

This validation task of the density models and associated packages of solar and magnetic indices or

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proxies consists in the estimation of precision/accuracy improvements in the satellite orbit determination. As a first step, specific satellites have to be selected to characterize different altitudes from 120 km to 1000 km. They may be satellites equipped with high precision geodesy tracking systems such as DORIS (SPOT satellite series), GPS (CHAMP, GRACE, DEIMOS-1...) or Satellite Laser Ranging but also satellites the orbits of which are tracked by radar with lesser precision. The satellites that were used in the model generation will also be re-used in the validation, but also spacecraft that were not used in order to validate externally.

Several types of orbit comparisons will be done: The first consists of satellite orbit determination using the available tracking data. The second type of comparison consists of short term extrapolation of the orbit, typically 1 to 3 days, which correspond to operational needs. The third one consists of a few weeks extrapolation and this corresponds to the need for operational planning of manoeuvres for example. The last test concerns long term extrapolation for mission analysis and is focused on integrated effects on altitude or semi-major axis over a solar cycle. The validation considers all cases of solar and geomagnetic activity from quiet to the worst and comparisons of the new density model to existing empirical models (JB2008, NRLMSIS00). This validation process is run twice, i.e., for DTM_2011 and DTM_2012. The results of the orbit tests are described in the documentation contained in the DTM model packages (see deliverables list).

Deliverables

Month 12:	D4.1. TLE-densities: Database and documentation of the TLE-inferred densities (By DMS, public)
Month 20:	D4.2. DTM_2011 model package. The model, benchmark and documentation (By CNES, public)
Month 32:	D4.3. DTM_2012 model package. The model, benchmark and documentation (By CNES, public)

4.5. WP5: Data assimilation for global analysis and near-real time prediction

Work package number	5	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Data assimilation for global analysis and near-real time prediction**				
Activity type	RTD				

Objectives

WP5 proposes two distinct yet complementary and mutually beneficial activities which will target data assimilation, the introduction of timely observation data into models in order to improve their predictions. DA-NRTP will address assimilation of thermospheric data into semi-empirical models for near-real time prediction. DA-GA aims to build capability for data assimilation into coupled thermosphere-ionosphere physical models to produce thermosphere-ionosphere global analyses for development of future operational systems (long-term potential advantages of an approach using physical models over one using semi-empirical models are outlined in section 2.3). These activities are:

[DA-NRTP] Develop a version of the DTM thermosphere model that can assimilate total density data in near-real time (DTM_nrt), which will make orbit predictions significantly more accurate (demonstrated to be 20-40% using a current model). Analyse methods to predict density using DTM (eg Kalman Filter). Users can install and run a version of DTM_nrt on-site. The model will be driven by a data file containing all parameters necessary for the density prediction. The production and distribution of this data file in near-real time is not an ATMOP objective.

[DA-GA] Develop a global analysis and forecast system for the thermosphere and ionosphere based on data assimilation into a physically evolving global forecast model. The impact on thermospheric analyses and forecasts of both assimilation of thermospheric observations and assimilation of ionospheric observations (via the coupling inherent in the physical model) shall be investigated and comparison of results with those from DA-NRTP made. The aim is to build capability for a future system which incorporates assimilation of a variety of thermosphere and ionosphere observations, in the manner of an operational meteorological system.

Description of work

WP5 will derive benefit from concurrent DA-NRTP and DA-GA activity in the initial stages by pooling effort required to understand, acquire and process different thermosphere observations. In later stages of the project, the aim will be to compare output from the two model systems, for instance to assess the extent to which the addition of ionospheric data impacts the evolution of the thermospheric forecast at different timescales. Production of an improved analysis state from the global system would allow experimentation to examine whether its use to initialise the semi-empirical model might improve predictions of the thermosphere in near-real time.

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Task 5.1 [DA-GA, DA-NRTP] Design of thermospheric data assimilation systems

Month 1- Month 3 (Partners: MET/CNES/UCL)

Finalize the design and structure of the thermospheric data assimilation systems. This shall include decisions on the length of assimilation window, the assimilation methods to be used[5], and selection of assimilation control variables (in the DA-GA assimilation system the control variables should have Gaussian error statistics, so the control variables may not necessarily match the physical model prognostic variables). Interaction with Task 3.1 is assumed here, when evaluating which version of the physical model (CMAT2) is best suited to be used in DA-GA.

For DA-GA, candidates for the assimilation method shall include:

☐ 4D-Var or PSAS (Physical Space Assimilation System) (like 4D-Var, but in observation

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[5] Instead of waiting until the start of the project to decide which DA method (e.g., 4D-Var, Kalman Filter) to use, we could decide right now to use 4D-Var and thus save resources. In addition, the Met Office weather forecasting DA system already uses 4D-Var, so it is easier to adapt this code to use 4D-Var for space weather than to completely write new code (for, e.g., KF) afresh.

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space rather than model space, so will be quicker to run if observations are sparse)

- Ensemble Kalman Filter (already used in some ionospheric assimilation applications. Quicker to set up (if no 4D-Var system exists already). Needs some tuning to get the ensemble perturbations right).

Task 5.2 [DA-GA] Observation processing and quality control

Month 4- Month 18 (Partners: MET/UCL)

Produce an observation processing system for the observations that shall be used in the assimilation system. The quality control system shall include gross error checks and other checks to ensure that the observations are acceptably close to forecast fields produced by the physical model. This step shall use observation errors supplied by the data providers. An estimate of forecast errors is also needed – a simplified form of this is acceptable, at least initially, although later the more detailed forecast errors provided by Task 5.4 may be used. The processed observations will be used in the data assimilation package (Task 5.4).

We intend here to add new thermospheric and ionospheric observations to the existing MET observations processing system which is used for weather forecasts. Therefore we shall be adding a new module to an existing system rather than writing a whole new system, and thus the work involved for this task is less than the reviewers may think.

Work package number	5	**Start date:**	T0	**End date:**	T0+36 months
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UCL shall examine the performance of the physical model with the addition of perturbations (observation minus model differences) calculated by the observation processing scheme.

This task has a dependency on delivery of the TLE densities (deliverable D4.1 from WP4 at M12).

Task 5.3 [DA-NRTP] Development of thermospheric data assimilation in DTM

Month 4- Month 18 (Partners: CNES/DMS)

The model corrections that can be estimated using mean densities from a varying number of objects tracked by the TLE radar data will be studied. The correction function can be daily scaling factors in the simplest case, or coefficients representing a low-resolution latitude and local time model additionally for example. The quality and spatial distribution (altitude, latitude, local time) of the mean density data available through radar data or TLE processing are essential to the ultimate complexity of the model. The optimum correction function taking into account the (distribution of) available observations will be established through simulations. Achievable model corrections for near-real time conditions as a function of TLE-data availability will be determined.

Task 5.4 [DA-GA] Thermospheric data assimilation using physical model

Month 10- Month 28 (Partners: MET/DMS)

Produce a data assimilation package which will combine quality-controlled observations (Task 5.2) with a forecast from a global physical thermosphere / ionosphere model (CMAT2 - WP3) to produce

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global analyses. There shall be both thermospheric and ionospheric control variables. The forecast model errors shall be calculated, probably using techniques already developed in meteorological data assimilation, such as using differences in forecast fields or ensembles of perturbed model runs.

The following provides further details on how the data assimilation package works.

The analysis works in a series of cycles, or time windows. Assuming a 6 hour cycle:

☐ Time = 0: combine quality-controlled observations (produced by Task 5.2) centred at time = 0 with a 6 hr model forecast run from analysis at time=-6 to calculate an "analysis increment". Add this increment to calculate analysis at time = 0;

☐ Time = 6: combine quality-controlled observations centred at time = 6 with a 6 hr forecast run from analysis at time = 0, to calculate an "analysis increment". Add this increment to calculate analysis at time = 6;

☐ Time = 12: combine quality-controlled observations at time = 12 with a 6 hr forecast from analysis at time = 6;

☐ and so on...

The analysis combines the observations and the model forecast using weights that are determined by

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the error covariances of the observations and the forecast. The observation error covariances will probably be supplied by the data suppliers. The forecast errors will be determined by the method detailed above.

Task 5.5 [DA-NRTP] Thermospheric data assimilation using DTM

Month 19- Month 34 (Partners: CNES/DMS/CLS)

The method of density prediction must be analysed as well. Tests performed a few years ago in the U.S and in Europe use an estimated constant correction function, which is subsequently applied for the following days. A Kalman filter may be a better choice to propagate the state of the atmosphere in the future. The DTM_2011 model algorithm must be adapted and modified in order to accommodate the selected correction function, and this version shall be named DTM_nrt. The parameters of the correction function, i.e., the variables that can be estimated in near-real time using the TLE data, must be applicable in the user version of DTM_nrt. If correction coefficients are not available (for whatever reason), the predicted density is identical to that of DTM_2011. The model shall also be operable under degraded conditions, i.e., if not all parameters of the correction function can be estimated. Activities to be undertaken are:

- ☐ Study prediction method (least-squares vs Kalman etc.)
- ☐ Implementation of new code

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- ☐ Development of DTM_nrt model package (install information, benchmark, and model documentation)

Task 5.6 [DA-GA, DA_NRTP] Assessment and Comparison of Thermospheric Data Assimilation results and preliminary integration of DA-GA quality control and assimilation modules

Month 28- Month 34 (Partners: MET/CNES)

Assess analyses and forecasts against independent observations, and perform comparisons of results from both DA-NRTP and DA-GA. Experiments with the DA-GA system shall focus on the separate impact of assimilating thermosphere and ionosphere observations on the thermosphere (in the latter case interaction between ionosphere and thermosphere comes via the physical forecast model and the improved ionospheric state supplied to it by the data assimilation system).

Initial experiments with DA-GA can be run for selected times, and there is no interaction between assimilation and model over time. A desirable, but not obligatory, further step is to integrate the observation processing and data assimilation modules (Tasks 5.2 and 5.4, respectively), into a demonstrator analysis and forecast system in which the cycles of quality control, assimilation, analysis and forecast can be carried out repetitively over any specified experiment period (e.g. for a few weeks). This is a stretching target but if achieved further experiments can be run for a selected period to examine the evolution of the analysis (including analysis errors) over time. New forecasts will be run each time and therefore, there is the dependency that an upgraded physical ionosphere / thermosphere

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model robust enough to deal with this should be produced in the framework of WP3.

Deliverables

Month 3:	D5.1. Finalize design of thermospheric data assimilation systems (Short report)
Month 18:	D5.2. Observation quality control package completed (Short report on design & performance) D5.3 Development of thermospheric data assimilation for DTM (Short report)
Month 28:	D5.4 Data assimilation package for DA-GA completed (Short report on design & performance)
Month 34	D5.5 DTM_nrt model package. The model, benchmark and documentation D5.6. Initial assessment and comparison of thermospheric analyses produced by both thermospheric data (Scientific publications on results)

4.6. WP6: Dissemination

Work package number	6	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Dissemination**				
Activity type	OTHER				

Objectives

This WP coordinates dissemination of results achieved in the project. The dissemination activities aim at (i) ensuring maximum awareness and visibility of the scientific achievements and results of the project, (ii) making known new developments that could be obtained as a part of the project results and encouraging their use, both scientifically and operationally. The ways to achieve these objectives are:

- ☐ develop a project web site for the dissemination of information on the project and its findings, for both internal and external use.
- ☐ ensure the dissemination of the project results to the scientific community and other interested parties;
- ☐ promote contacts with potential users of the thermosphere model developed in the frame of the project.

To obtain as much exposure of the project as possible, across all the areas, several forms of dissemination media will be used to achieve the objectives: website, brochures and presentations, scientific publications and press release.

Description of work

Task 6.1 ATMOP Website setup and maintenance

Month1-Month36 (Partners: Kybertec/DMS/CNRS)

T 6.1.1: Design, development, and implementation of a Web server for information (public and project internal) dissemination and management. It will be set up by a specialized organization (Kybertec), so as to achieve a high standard web site. Relevant information about the project and results of WPs will be made publicly available through this website, so as to enhance timely dissemination of intermediate and final results.

In particular, the proxies and the semi-quantitative thermosphere model (DTM_2011, DTM_2012 and DTM_nrt) developed in the frame of the project will be made available through the ATMOP web site so that it will be possible to run on-line the thermosphere model produced in the framework of the project. This task includes the development of mechanisms for data export and interactive running of models. This can be achieved by means of links to remote websites (of contributing institutions), when requested in WP activity descriptions. In this latter case, the software will be developed by Kybertec and implemented by Kybertec on the remote websites.

T 6.1.2: Maintenance of the website will also be performed by Kybertec.

Task 6.2 Brochures and Presentations (leaflets, PowerPoint presentations, etc.)

Month1-Month36 (Partners: all, with CNRS coordination)

Communication of the scientific results to partners, to the scientific community and to users of the thermosphere model.

Work package number	6	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Dissemination**				
Activity type	OTHER				

Objectives

This WP coordinates dissemination of results achieved in the project. The dissemination activities aim at (i) ensuring maximum awareness and visibility of the scientific achievements and results of the project, (ii) making known new developments that could be obtained as a part of the project results and encouraging their use, both scientifically and operationally. The ways to achieve these objectives are:

- ❑ develop a project web site for the dissemination of information on the project and its findings, for both internal and external use.
- ❑ ensure the dissemination of the project results to the scientific community and other interested parties;
- ❑ promote contacts with potential users of the thermosphere model developed in the frame of the project.

To obtain as much exposure of the project as possible, across all the areas, several forms of dissemination media will be used to achieve the objectives: website, brochures and presentations, scientific publications and press release.

A number of different kinds of **publicity material** such as PowerPoint presentation templates aiming at scientists and at potential users, **brochures** addressing different levels of expertise are needed to address different partners and users of the thermosphere model. This WP will act as a coordinator with other WPs to identify the required range of publicity material, for appropriate and efficient communication to potential users of the outcomes of the project.

This WP will act as coordinator with other WPs to design and disseminate publicity materials. Kybertec will be in charge of the generation of such materials.

The semi-empirical model is more a practical tool for commercial and scientific use so dissemination would be tied more to getting the scientific and technical communities to use it. Because our study is so specific, these targeted users will benefit much more from it than the general public. In particular, contacts with satellite operators will be proposed when appropriate near the end of the ATMOP project, in order to inform possible users and promote the use of the model. We are for instance considering the possibility of actions related to the training of engineers/scientists who work in that field, e.g. at EDA-Darmstadt. The military should be included, but the training may then have to be organised on a national level, in those countries only that have space agencies.

Task 6.3 Communications at scientific conferences, and publication in scientific journals

Month1-Month36 (Partners: all, with CNRS coordination)

The results of different WPs will be presented under the responsibility of their respective leaders through communications at national and international conferences, publications in peer-reviewed journals, and dissemination of results among stakeholders in Europe. Associated part of the dissemination plan will be created.

Task 6.4 Engagement with press

Month1-Month36 (Partners: all, with DMS coordination)

The consortium will produce at least one final press release. Associated part of the dissemination plan will be created.

Work package number	6	**Start date:**	T0	**End date:**	T0+36 months
Work package title	**Dissemination**				
Activity type	OTHER				

Objectives

This WP coordinates dissemination of results achieved in the project. The dissemination activities aim at (i) ensuring maximum awareness and visibility of the scientific achievements and results of the project, (ii) making known new developments that could be obtained as a part of the project results and encouraging their use, both scientifically and operationally. The ways to achieve these objectives are:

- ☐ develop a project web site for the dissemination of information on the project and its findings, for both internal and external use.
- ☐ ensure the dissemination of the project results to the scientific community and other interested parties;
- ☐ promote contacts with potential users of the thermosphere model developed in the frame of the project.

To obtain as much exposure of the project as possible, across all the areas, several forms of dissemination media will be used to achieve the objectives: website, brochures and presentations, scientific publications and press release.

Deliverables

Month 6:	D6.1 Prototype of ATMOP Website (by KYBERTEC, Prototype/Public)
	D6.2 Provisional Dissemination and Exploitation Plan (by DMS, Report/Restricted)
Month 36	D6.3 Dissemination and Exploitation Plan (by DMS, Report/Restricted)
	D6.4 ATMOP Web site: Final Implementation (by KYBERTEC, Prototype, Public)
	D6.5 ATMOP website: CD with all documentation and software for website installation on any platform

END OF DOCUMENT