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Satellite Observations for Identifying Continental-Scale Climate Change over Australia

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With 4 Figures

Abstract

Australia's large extent and relatively low population density, as well as its range of climates, means that it is heavily dependent upon satellite observations to identify the extent and magnitude of climate change. This work examines three types of satellite missions that are used to assess different aspects of climate change. The first involves the use of radio occultation measurements based on signals from Global Navigation Satellite Systems (GNSS) spacecraft made by low-Earth orbiting (LEO) satellites to identify changes in the height of the tropopause, a sensitive indicator of climate change owing to its response to temperature changes in the troposphere and lower stratosphere. The second deals with rainfall over Australia, as measured by the Tropical Rainfall Monitoring Mission (TRMM), in conjunction with other satellite- and ground-based observations. Such observations are invaluable, given the scarcity of ground-based observations over vast areas of Australia. While a comparison between the TRMM product and existing ground-based data is very good, there appears to be a decrease in the correlation between datasets, the reason for which is still being investigated. Finally, we examine the state of terrestrial water storage over Australia as determined from variations in the regional gravity field as measured by the Gravity Recovery and Climate Experiment (GRACE) twin-satellite mission. The loss of substantial volumes of ground water from the Murray-Darling River Basin in the southeast corner of the continent is very apparent, as is an increase over the northern parts of the country. Together, such satellite missions provide a continental-scale picture of climate change over Australia, with temperature and rainfall variations, as well as water resources, able to be monitored, providing valuable information to natural resource managers and climate modellers who endeavour to predict future changes.

Zusammenfassung

Aufgrund seiner großen räumlichen Ausdehnung sowie geringen Bevölkerungsdichte ist die terrestrische Beobachtung von Klimaänderungen über dem australischen Kontinent recht schwierig. Deshalb ist Australien stark von Satellitenbeobachtungen abhängig, um seine diversen Klimazonen adäquat zu erfassen. Diese Arbeit untersucht Beobachtungen von drei verschiedenen Satellitenmissionen auf ihre Anwendung für Klimawandelstudien über Australien. Die erste Untersuchung benutzt Radiookkultationsbeobachtungen von GNSS (*Global Navigation Satellite System*)-Radiosignalen, die durch die Erdatmosphäre gehen und von verschiedenen niedrig fliegenden Satelliten empfangen werden. Diese Beobachtungen sind dazu geeignet, um Änderungen in der Tropopausenhöhe zu untersuchen, die wiederum ein guter Indikator für Klimaänderungen aufgrund von Temperaturänderungen in der Troposphäre und unteren Stratosphäre sind. Die zweite Untersuchung basiert auf den Niederschlagsprodukten der *Tropical Rainfall Monitoring Mission* (TRMM) in Verbindung mit terrestrischen Beobachtungen des australischen *Bureau of Meteorology* (BOM). Hierbei werden TRMM-Satellitenbeobachtungen verwendet, um die teilweise spärliche Beobachtungsdichte der BOM-Daten zu ergänzen. Vergleiche haben gezeigt, dass die TRMM- und BOM-Niederschlagsprodukte generell sehr gut miteinander korrelieren, allerdings mit einer zurzeit unerklärten geringen Reduktion der Korrelation in den letzten Jahren. Die dritte Untersuchung analysiert kontinentale Hydrologieänderungen über Australien, die auf regionalen Änderungen des Erdschwerefeldes basieren und durch die *Gravity Recovery and Climate Experiment* (GRACE)-Satellitenmission beobachtet wurden. Diese zeigt über die letzten Jahre einen Massenverlust über dem Einzugsgebiet des Murray-Darling und einen starken Massengewinn im tropischen Norden von Australien. Diese Arbeit demonstriert, dass alle betrachteten Satellitenmissionen die Auswirkungen von kontinentalen Klimaänderungen, wie Änderungen in Temperatur, Niederschlag und Wasserressourcen, erfassen können. Damit können für öffentliche und private Planer wichtige Informationen für zukünftigen Klimamodellierungen bereitgestell werden.

1. Introduction

Australia is a land of contrasting climates, both across its extent and from year to year as the seasons vary from deluge to drought. However, with increasing public concern and some scientific evidence pointing towards climate change (e.g., NICHOLLS 2006), the need to quantify climate change over the breadth of the country is important. This has become more relevant to Australia in recent years, with notable events such as the devastating bushfires and dust storms over eastern Australia in 2009, and the contemporary drought, also known as *the big dry* (MURPHY and TIMBAL 2008, UMMENHOFER et al. 2009), which is still afflicting many areas of Australia, despite other parts (e.g., Queensland) experiencing major flooding.

The climate of Australia, while dominated in terms of area by the inland arid regions, nonetheless shows a wide variability, ranging from tropical to temperate. This leads to the likelihood that different parts of the continent could experience climate change differently. However, a major problem arises from the very heterogeneous population density, concentrated mainly along the coastal areas, the southeast and southwest, leading, in turn, to a heterogeneous distribution of meteorological recording stations. This is shown in Figure 1, where Figure 1*A* describes the climate of Australia, following the modified Köppen-Geiger climate classification scheme of PEEL et al. (2007), while Figure 1*B* shows the distribution of currently operating Bureau of Meteorology (BOM) weather-reporting sites (see the BOM website, http://www.bom.gov.au). The most obvious point is the concentration of stations in the more temperate and densely populated areas. However, while the less instrumented areas tend to be in arid regions, a large proportion of the tropical part of the country also has few recording stations. Therefore, Figure 1 shows that there are areas both in need of the observations provided by Earth observation satellites (EOS), as well as areas sufficiently instrumented to allow ground-truth comparisons.

Australia has long been a significant user of the products of EOS, a result of our relatively low population, vast area, long coastline and extensive Exclusive Economic Zone, combined with serious vulnerability to a wide range of natural hazards. A recent report prepared by the Australian Academy of Science and the Australian Academy of Technological Sciences and Engineering stated that "Earth observations from space are the single most important and richest source of environmental information for Australia" (*Australian Academy of Science* 2009). Such observations are not only of benefit to assessing climate change, but also for addressing issues involving water resources, forestry, agriculture, transport and energy, natural disaster mitigation and national security.

In this paper, we examine three series of EOS observations that allow for continental-scale, and potentially smaller-scale, views of climate change over Australia. Each of these employs different satellites, some built for very specific purposes, while others are designed to have a wider range of applications. While there are many more applications of observations from EOS, these examples provide an overview of the sort of issues that may be dealt with by EOS observations within the context of Australian climate change. The climatic issues of interest in this work are as follows:

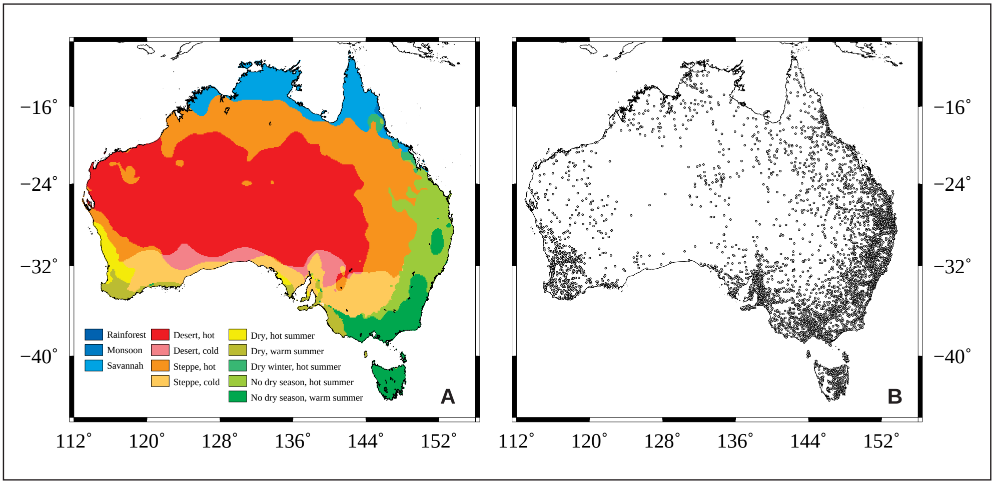

Fig. 1 (*A*) Climate zones of Australia, as described by a modified Köppen-Geiger climate classification scheme (Peel et al. 2007). (*B*) Locations of weather-reporting stations.

– Estimates of tropopause parameters (e.g., height, temperature), based on low-Earth orbiting (LEO) satellites receiving occultation signals from Global Navigation Satellite System (GNSS) spacecraft (Melbourne et al. 1994);
– Precipitation, as described for the purpose of this study, by products from the Tropical Rainfall Measuring Experiment (TRMM; Kummerow et al. 1998, 2000), and compared to ground-based measurements;
– Terrestrial water storage, as determined from changes in the Earth's gravity field observed by the Gravity Recovery and Climate Experiment (GRACE; Tapley et al. 2004).

We outline in the following some background of each of these topics with respect to the satellites involved, showing some examples from each of how these parameters are changing. We then conclude with some comments about other recent and future missions that could benefit climate change studies in Australia.

2. Observations of the Tropopause by low-Earth Orbiting Satellites

The tropopause is one of the most fundamental units of the atmosphere, representing the boundary between the troposphere, the lower-most portion of the atmosphere where we live, and the stratosphere. The tropopause is considered to be a potentially useful measure of climate change, being sensitive to temperatures in the lower atmosphere (e.g., Sausen and Santer 2003). For example, anthropogenic greenhouse gas concentration increases have been proposed to have caused around 80 % of the global tropopause height increase between 1979 and 2001 (Santer et al. 2003).

Traditionally, tropopause parameters have been measured using radiosonde (balloon) observations. However, in recent years, the use of LEO satellites that observe the change in signals from GNSS satellites as they rise or set behind the atmosphere (occulting satellites, or GPS-RO measurements) has opened up new opportunities to monitor the atmosphere, especially the tropopause. The main advantage of GPS-RO observations is that they are global, unlike radiosondes where the oceans are largely neglected, and all-weather.

A number of studies have compared radiosonde observations and the estimates of atmospheric parameters inferred from GPS-RO and – in general – the agreement has been very good (e.g., Schmidt et al. 2005, Fu et al. 2007, Khandu et al. 2010). There are a number of LEO satellites providing GPS-RO observations, in particular CHAMP (launched 15th July, 2000), SAC-C (21st November, 2000), GRACE (17th March, 2002), COSMIC (15th April, 2006), MetOp (19th October, 2006), and TerraSAR-X (5th June, 2007) (Wickert et al. 2009).

For Australia, Fu et al. (2007) and Khandu et al. (2009) have verified that GPS-RO measurements are of an equivalent quality to radiosonde data. Khandu et al. (2010), making use of CHAMP, GRACE and COSMIC GPS-RO observations, investigated how the tropopause was varying over Australia. This is shown for the continent as a whole in Figure 2, where we present the rate of change in tropopause height (Figure 2*A*) and temperature (Figure 2*B*). Given the data density currently possible with the number of GPS-RO satellites operating, one can see how continental-scale climate change could be monitored using such observations.

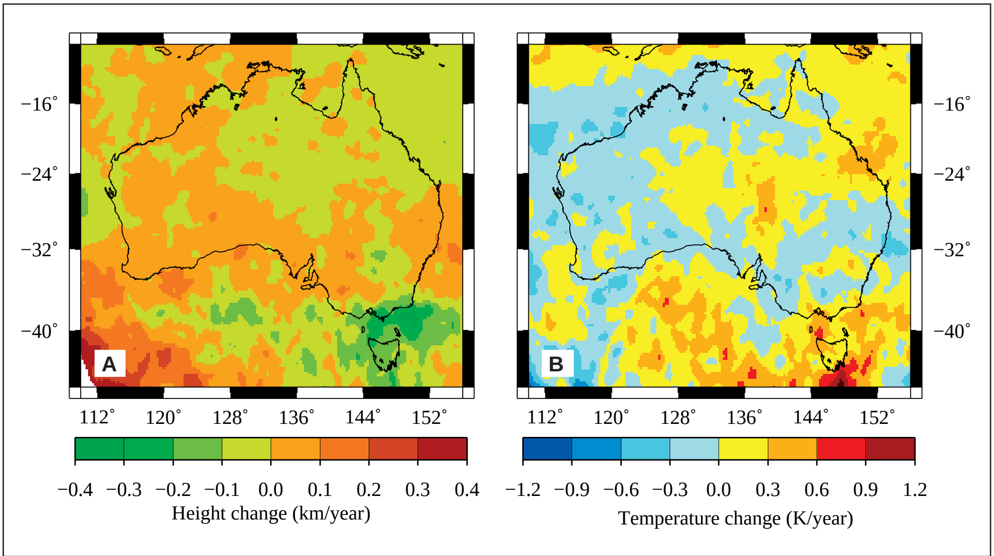

Fig. 2 Changes in the tropopause over Australia as identified by a combination of GPS-RO data (*A*) Elevation, (*B*) temperature (adapted from Khandu et al. 2010).

3. Precipitation from the Tropical Rainfall Measuring Mission

Precipitation is one of, if not the most, important climatic indicator for society to consider. Given the still-existing drought conditions in many parts of Australia, this leads to concerns such as the effect droughts have on the national economy since it adversely affects agriculture and the cost of living, as well as governmental responses such as the construction of desalination plants for coastal urban centers. Nicholls (2006) reports that annual rainfall has increased in the northwest of Australia (mainly during summer), and has decreased along the east of the continent and in the southwest, where the changes have been in winter for the southwest and southeast, and in summer in the northeast.

As mentioned in the Introduction, the distribution of weather-reporting stations is very heterogeneous. Hence, the possibilities offered by satellite-based precipitation measurements become very attractive. The example of such a mission discussed in this work is TRMM, a joint mission between the United States (NASA) and Japan (Japan Aerospace Exploration Agency, JAXA). TRMM was launched on the 27th November 1997 from the Tanegashima Island space center and orbits at an altitude of ca. 403 km with an inclination of 50°, completing 16 revolutions per day (TRMM webpage, http://trmm.gsfc.nasa.gov). The objective of TRMM is to measure rainfall and energy exchange over the tropical and subtropical regions of the world, in particular covering oceans and un-sampled land (Kummerow et al. 1998, 2000).

One aspect of such data is the need for it to be validated by ground-truth data, and this has been carried out for the TRMM products (e.g., Kummerow et al. 2000). Such efforts are currently being undertaken for Australia at Curtin University of Technology, Perth, where we are comparing TRMM results (the TRMM and other satellites' precipitation products, Huffmann et al. 2007) with a similar dataset provided by the Australian Bureau of Meteorology (BOM). Figure 3 shows an example of such a comparison, where Figure 3*A* presents the cross correlation between the two datasets for the period 1998 to 2009. There is generally an excellent correlation, except where there is a lack of ground-truth data (cf. Figures 3 and 1*B*). However, this correlation varies over time, as shown in Figure 3*B* for only those grid cells where there was a BOM recording station, with possibly an increase in scatter of the correlation between datasets being noted. The reasons behind this are currently under investigation.

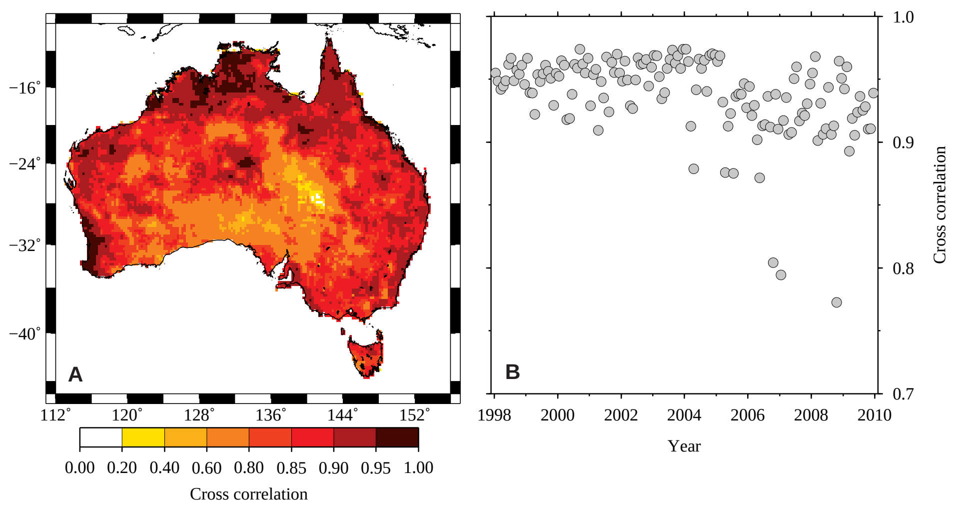

Fig. 3 Variation in the cross correlation between the TRMM and BOM datasets over Australia for the period 01. 1998 to 12. 2009. (*A*) The cross correlation over Australia as a whole. (*B*) The temporal change in the cross correlation.

4. Terrestrial Water Storage from the Gravity Recovery and Climate Experiment

The GRACE satellite mission is a joint United States (NASA) and German (*Deutsches Zentrum für Luft- und Raumfahrt*) mission (Tapley et al. 2004). Its aim is to resolve spatial and temporal changes in the Earth's external gravity field to allow mass exchanges between the atmosphere, cryosphere and hydrosphere to be quantified.

GRACE was launched on the 17th March, 2002, from the Pletsetsk space center, Russia. It consists of two spacecrafts in the same near-polar orbit of inclination 89.5° with an initial altitude of ca. 500 km. The satellites are separated by ca. 220 km, and their distance apart is measured using a K-band range rate system (Tapley et al. 2004). In addition, each satellite carries a GPS receiver, the data from which is used for precise orbit determination, as well as satellite laser ranging reflectors for very precise orbit determination for some arcs. The mission initially had an expected design lifespan of five years, although there are some expectations that it will continue until around 2013 (Chen et al. 2006).

In terms of the major sources of spatio-temporal gravity field change, Australia is relatively 'quiet', given the lack of major tectonic processes within the continent's boundaries and that it did not experience significant glaciation during the Last Glacial Maximum, some 21,000 years ago. Therefore, any gravity field changes observed over Australia (after correcting for the effects of the oceans and atmosphere) are dominated by changes in terrestrial water storage, be they surface waters (lakes, rivers, etc.), groundwater or soil moisture.

However, when one considers Australia's broad aridity and recent drought conditions, a relatively small hydrological signal is expected (with the exception of the tropical north). This makes the detection of terrestrial water-storage variations by gravity-field changes a significant challenge (e.g., Awange et al. 2009). Nonetheless, a number of efforts have been made to exploit GRACE observations for the Australian situation. For example, for the Murray-Darling River Basin (MRDB), the most important agricultural region in Australia, Ellett et al. (2006) commented that GRACE would be suitable for hydrological studies owing to the dominance of groundwater variations in the inter-annual water-storage signal. This was verified by Leblanc et al. (2009) who, by combining GRACE estimates with hydrological observations and modeling results, estimated a loss of groundwater from this region of the order of 104 km^3 between 2001 and 2007.

An example of how results from GRACE can be used is shown in Figure 4. Here, we make use of the latest release from the Center for Space Research at the University of Texas, Austin (Bettadpur 2007), acknowledging that several others are available. Figure 4 shows the linear trend (Figure 4*A*) and the annual cyclic amplitude (Figure 4*B*) in the gravity field, expressed as equivalent water thickness (EWT) (a common measure in GRACE hydrological studies, e.g., Wahr et al. 1998). By way of comparison, we include the same temporal behavior, but for terrestrial water storage as predicted by a hydrological model (WGHM, Döll et al. 2003).

From these linear trends, one can see in the GRACE results a general decrease in EWT in the southeast of the continent around the MRDB, while in the tropical north, there is an increase. Similarly, the annual (seasonal) cycle in terrestrial water storage is apparent. We compare this to the hydrological model to show that, while there are differences and similarities between the two, one can envisage (as has been done, e.g., by Güntner 2008) how GRACE results could be used to assess hydrological models.

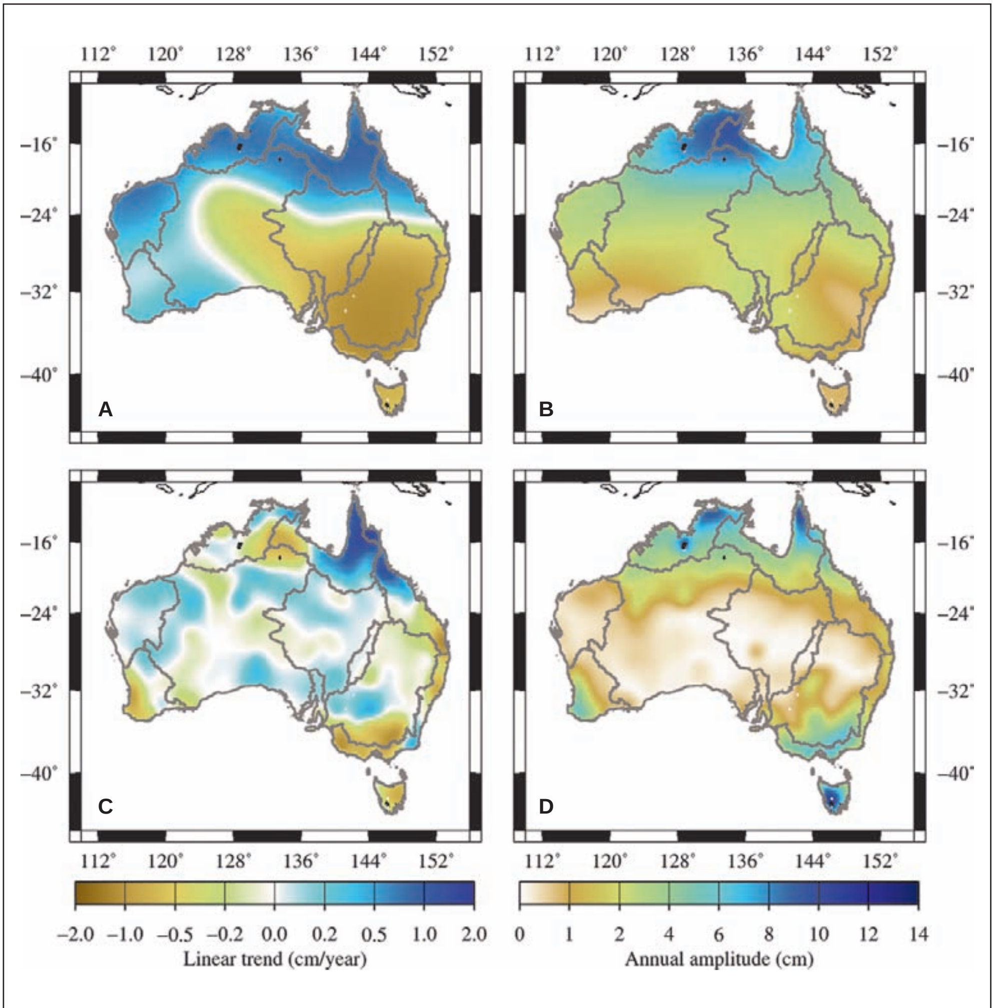

Fig. 4 Temporal trends in the CSR GRACE and WGHM time-series in equivalent water thickness (EWT). (*A*, *B*) GRACE linear and annual cyclic terms. (*C*, *D*) The same, but for the WGHM hydrological model. The internal boundaries define the major river basins.

5. Concluding Statements

There are a number of recently and soon-to-be launched EOS missions that have the potential to directly benefit climate-change studies over Australia. Some examples are

– The Soil Moisture and Ocean Salinity (SMOS) mission, launched on the 2nd November 2009, by the European Space Agency (ESA). This aims to measure soil moisture over the Earth's land masses and ocean salinity. Both of these parameters are essential for climate change studies, with soil moisture being an integral part of continental hydrology, while salinity plays an important role in ocean circulation (e.g., Antonov et al. 2002).

– CryoSat-2, the substitute mission for the original CryoSat mission that suffered a catastrophic launch failure in November 2005, is expected to be launched in early 2010. Its purpose is to measure the change in the thickness of land-based and sea ice. In measuring the changes in land-based ice, constraints may be placed on this contribution to sea-level change, another area of concern for Australia, in terms of inundated land area, the intrusion of seawater into freshwater aquifers, and the potential security issues arising from the dangers sea-level rise will inflict on low-lying Pacific nations.
– Another mission that would contribute greatly is a follow on to GRACE. There are plans for such a mission, however, planning is still in progress. As discussed, GRACE has been used to examine changes in terrestrial water storage (e.g., Awange et al. 2009) as well contributing to the improvement of hydrological models.

One of the comments made in the report from the *Australian Academy of Science* (2009) was that Australia should develop a national strategy to secure long-term access to data from EOS missions, as well as to strengthen our capabilities in the various aspects (data acquisition, processing, research, education, etc.) of such missions. The report was received positively by the Ministry for Innovation, Industry, Science and Research, and it is hoped that Australia's involvement in EOS missions will increase in the near future.

Acknowledgements

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Medicine at the Interface between Science and Ethics

Leopoldina-Symposium

vom 30. Mai bis 1. Juni 2007 in Weißenburg, Bayern

Nova Acta Leopoldina N. F. Bd. *98*, Nr. 361
Herausgegeben von Walter Doerfler (Erlangen/Köln), Hans-G. Ulrich (Erlangen) und Petra Böhm (Köln)
(2010, 258 Seiten, 31 Abbildungen, 4 Tabellen, 23,95 Euro,
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Naturwissenschaft und Theologie/Ethik versuchen mit unterschiedlichen Konzepten, ein Weltbild zu erfassen, das die *conditio humana* besser zu verstehen erlaubt. Die Fragen sind weit gefasst; endgültige Antworten wird man nicht leicht finden. Gemeinsame Diskussionen über diese Probleme könnten beiden Gebieten Anregungen geben und der Biomedizin im Umgang mit der sehr kritischen Öffentlichkeit helfen. Voraussetzung ist Offenheit gegenüber der anderen Denkweise. Der vorliegende Band behandelt daher aus der Perspektive von Naturwissenschaftlern und Ethikern so verschiedene Themen wie die neuen Herausforderungen an Moral- und Ethikdiskurse durch die jüngsten Fortschritte der Biowissenschaften, die Grenzen der ethischen Reflexion bei den neueren Entwicklungen der Molekularbiologie, die Geschichte der Auffassungen vom „Gen" und seiner Bedeutung in der Humanbiologie, aber auch die Missverständnisse zwischen den beiden Kulturen der Naturwissenschaften und der Geisteswissenschaften in der Forschung über Lebensprozesse. Dazu kommen Beiträge zur Stammzellproblematik, der Verwendung von Tiermodellen in der Translationsmedizin, über Würde von Zellen in Kultur, Fragen der Pluripotenz von Zellen und der Reprogrammierung von Zellkernen sowie der Bedeutung von Methylierungsmustern für die Epigenetik. Die Beiträge sind in englischer oder deutscher Sprache verfasst.

Wissenschaftliche Verlagsgesellschaft mbH Stuttgart

Die Gründung der Leopoldina
–*Academia Naturae Curiosorum* – im historischen Kontext
Johann Laurentius Bausch zum 400. Geburtstag

Leopoldina-Symposium

vom 29. September bis 1. Oktober 2005 in Schweinfurt (Bibliothek Otto Schäfer)

Acta Historica Leopoldina Nr. 49
Herausgegeben von Richard Toellner (Kloster Amelungsborn), Uwe Müller (Schweinfurt), Benno Parthier und Wieland Berg (Halle/Saale)
(2008, 336 Seiten, 42 Abbildungen, 22,95 Euro, ISBN: 978-3-8047-2471-6)

Ziel dieser interdisziplinären, internationalen Tagung war es, die Gestalt des Johann Laurentius Bausch (1605–1665) in ihren biographischen, sozialen und wissenschaftsgeschichtlichen Bedingungen darzustellen sowie die Gründung der Leopoldina in den Rahmen der internationalen Akademiengeschichte des 17. Jahrhunderts einzuordnen. Es wurde der über die bisherige Literatur hinausgehende aktuelle Forschungsstand in neun Vorträgen präsentiert, die der vorliegende Band in erweiterter und aktualisierter Form dokumentiert und vertieft durch Anhänge mit der Edition der Leges der Akademie und Bibliographien der im frühen Akademieprogramm veröffentlichten Monographien und ihrer Vorgänger aus anderthalb Jahrhunderten sowie einer Analyse der Selbstdarstellung der Leopoldina in ihrer Korrespondenz mit der Royal Society von 1670 bis 1677.

Wissenschaftliche Verlagsgesellschaft mbH Stuttgart

Der Briefwechsel von Johann Bartholomäus Trommsdorff (1770–1837)

Lieferung 11: Trott – Ziz und Nachträge

Acta Historica Leopoldina Nr. *18*/11
Bearbeitet und kommentiert von Hartmut Bettin (Marburg), Christoph Friedrich (Marburg) und Wolfgang Götz (Wildeshausen), unter Mitarbeit von Henriette Bettin (Greifswald)
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Trommsdorff gilt als Vater der wissenschaftlichen Pharmazie. Der Begründer des *Journals der Pharmacie* engagierte sich in standes- und sozialpolitischen Fragen. Seine umfangreiche Korrespondenz spiegelt die Entwicklung von Chemie und Pharmazie im beginnenden 19. Jahrhundert, aber auch die Veränderungen des Apothekenwesens seiner Zeit wider. Die Edition (über 250 Briefpartner und 1500 erhaltene Briefe) stellt eine bedeutende wissenschaftshistorische Quelle dar. Mit dieser Lieferung wird der kommentierte Briefwechsel J. B. Trommsdorffs abgeschlossen. Schwerpunkte bilden die Briefe des Anilin-Entdeckers und Trommsdorff-Schülers Otto Unverdorben und die Briefe des Chemie- und Pharmazieprofessors Heinrich August Vogel. Darüber hinaus enthält der Band zahlreiche Briefe von oder an bedeutende Ärzte und Apotheker, berühmte Chemiker und Naturforscher sowie hochgestellte Persönlichkeiten, beispielsweise Herzog Carl August von Sachsen-Weimar-Eisenach und nachgetragene Briefe Johann Wolfgang Döbereiners, August Peter Julius Du Mênils sowie Johann Friedrich Gmelins. Der Anhang enthält Familien-Stammbäume zur Orientierung sowie Gesamtsachregister und -verzeichnisse über alle 11 Lieferungen.

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