Institution: University of Reading

Unit of Assessment: 7 Earth Systems & Environmental Sciences

Title of case study: TRACK: identifying storms in meteorological data for quantitative analysis

1. Summary of the impact:

Research within the Unit was used to create the "TRACK" storm-tracking and analysis software package, which is used to automatically identify storms from both observed and simulated weather data. The software has been used in academic research to improve understanding of how storms develop and how they may change over time, but TRACK has also found widespread applications outside academia. It has been used to quantify errors in current operational weather forecasts, enabling users to produce more accurate storm forecasts better tailored to their needs. It has been used to develop catalogues of historical storms used in the insurance industry for risk assessment. TRACK has also been used to evaluate the performance of climate models and inform their development and improvement.

2. Underpinning research:

Across the world, damaging extreme weather such as high winds and flooding is frequently associated with storms. In order for them to be systematically studied, they need to be defined objectively and consistently from observed weather data. Given the social and economic impact of severe storms, it is also important to assess how well operational weather forecast and climate models represent storms; the complex and fine scale nature of storm processes are a challenge to represent in even the best high grid resolution models. However, the petabyte-scale volumes of data involved make traditional manual approaches to the identification of storms impossible. Scientists working in the Unit have therefore created a unique automated diagnostic tool to identify storms, track their movement and evolution, and record their characteristics (intensity, growth rates etc.). The methodology was based on the Unit's research into storm phenomena, and applies image processing techniques to existing and novel data from weather and climate models and observations[12-15]. The research was led by Senior Research Fellow K. Hodges (who has been with the Unit since before 1993), with support from other Unit staff members B. Hoskins (also a Unit member since before 1993, since 2008 at 0.2FTE), P-L. Vidale, L. Shaffrey, O.L. Bengtsson, C. Thorncroft and H. Dacre, by Knowledge Exchange Fellows R. Cornforth E. Froude and J. Strachan (funded by NERC, NERC and Willis-Re, respectively), by PDRA Zappa, and by several PhD students supervised by Unit staff. All these scientists are still with the Unit except the PhD students and Thorncroft, Froude and Strachan (who left in 2002, 2013 and 2013, respectively).

That the TRACK software is highly flexible and of wide application has been demonstrated by its use in a long series of studies of a wide range of storm types including: tropical cyclones (hurricanes and typhoons);[1,2] extratropical cyclones (such as the windstorms which affect UK and western Europe);[3-7] "polar low" cyclones (high latitude cyclones that are a hazard to high-latitude shipping and gas and oil platforms);[8] and the development of African Easterly Waves (elongated troughs of low pressure moving westward across tropical Africa, and precursors of many tropical cyclones).[9] The Unit extended the output of TRACK to include the 3-dimensional structure of all these storm types and their impact "footprint" in surface winds, temperatures, and precipitation.

Unit research using TRACK has shown that storm systems in most operational weather-forecast models, on average, move too slowly,[18] creating important insights for both model development and forecast operations. The use of TRACK with data from climate models used to simulate future climate has shown that increased model-grid resolution is vital to accurately represent storm properties.[2,3,6] It has also shown that whilst the frequency of winter extra-tropical cyclones is projected to fall in the future across most of Europe, it may increase across the UK and central Europe.[4] TRACK has been used to reconstruct historical storms to aid in their interpretation [16,17], and has been used to construct storm databases[10,11]. It was also integral to the first comprehensive evaluation of the statistical properties of Africa Easterly Waves.[9]

Applications in scientific research and developments of TRACK

[1] O.L. Bengtsson, K. I. Hodges, et al. (2007) How may tropical cyclones change in a warmer climate?, Tellus, V59A, 539-561. doi: 10.1111/j.1600-0870.2007.00251.x

[2.] J. Strachan, et al. (2013) Investigating global tropical cyclone activity with a hierarchy of AGCMs: the role of model resolution. *J. Clim*., 26, 133-152, doi:10.1175/JCLI-D-12-00012.1

[3.] O.L.Bengtsson, (2009) Will Extratropical Storms Intensify in a Warmer Climate? *J. Clim.*, 22 (9).

2276-2301. doi: 10.1175/2008JCLI2678.1
[4] G. Zappa et al (2013) A Multimodel Assessment of Future Projections of North Atlantic and European Extratropical Cyclones in the CMIP5 Climate Models J. Clim 26, 5846-5862.
[5.] Y. Zhang et al. (2012) A Climatology of Extratropical Cyclones over East Asia During 1958-2001. Acta Meteorologica Sinica 26, 261-277 doi: 10.1007/s13351-012-0301-2
[6.] J. Catto, et al. (2010) Can climate models capture the structure of extratropical cyclones? *J.Clim.*, 23(7), 1621-1635. doi: 10.1175/2009JCLI3318.1
[7.] K. Hodges, et al. (2011**)** A Comparison of Extratropical Cyclones in Recent Reanalyses ERA-Interim, NASA MERRA, NCEP CFSR, and JRA-25**.** *J. Clim*., 24, 4888-4906
[8.] L. Xia, et al. (2012) A comparison of two identification and tracking methods for polar lows, *Tellus Series A:*, 64. 17196. doi: 10.3402/tellusa.v64i0.17196
[9.] C. Thorncroft and K. Hodges (2001) African easterly wave variability and its relationship to Atlantic tropical cyclone activity. *J. Clim.*, 14 (6). 1166-1179. doi: 10.1175/1520-0442
[10.] H. Dacre, et al. (2012) An extratropical cyclone database: A tool for illustrating cyclone structure and evolution characteristics. *BAMS*, 93. 1497-1502. doi: 10.1175/BAMS-D-11-00164.1
[11.] Extreme Windstorms Catalogue: http://www.met.reading.ac.uk/~extws/

3. References to the research:

The development of TRACK is detailed in sequence of 70 journal publications since the first in 1994.[12] A WoS search (October 2013) reveals over 2700 citations to these papers. The 7 below are selected to mark key stages of this long development. Three that can be used to demonstrate science quality are marked with an asterisk. Note that of studies discussed above[1-11], all but one[5] also report work done within the Unit (although TRACK is also widely used elsewhere in the academic community). Development has been funded as a part of a series of large NERC grants that made use of TRACK. Recent examples are NE/I018891/1 (NERC impact accelerator with BMT, £67k), NE/I005242/1 (£0.31M), and NE/I00520X/1 (£0.83M). Earlier competitively-won core funding for the development of TRACK came as part of NUTIS (1993-1998), ESSC (1998-2006) and NCEO (2006-present), an estimated total support exceeding £1.5M.

[12.] *K.Hodges (1994) A general-method for tracking analysis and its application to meteorological data, *Mon. Wea. Rev.*, 122 (11), 2573-2586. doi: 10.1175/1520-0493 (116 cites)
[13.] *K.Hodges (1995) Feature tracking on the unit-sphere, *Mon.Wea.Rev.*,123(12), 3458 (93 cites)
[14.] K.Hodges (1996) Spherical nonparametric estimators applied to the UGAMP model integration for AMIP. *Mon. Wea. Rev.*, 124, 2914-2932. doi: 10.1175/1520-0493 (55 cites)
[15.] K.Hodges (1999) Adaptive constraints for feature tracking, *Mon. Wea. Rev.*, 127 (6), 1362-1373, doi: 10.1175/1520-0493 (76 cites)
[16.] *B.Hoskins and K.Hodges (2002) New perspectives on the Northern Hemisphere winter storm tracks, *J. Atmos. Sci.*, 59 (6),1041-1061 doi: 10.1175/1520-0469 (267 cites)
[17.] B.Hoskins and K.Hodges (2005) A new perspective on Southern hemisphere storm-tracks, *J Clim.*, 18 (20), 4108-4129. doi:10.1175/JCLI3570 (101 cites)
[18.] L.Froude, et al. (2007) The Prediction of Extratropical Storm Tracks by the ECMWF and NCEP Ensemble Prediction Systems, *Mon. Wea. Rev.*, 135 (7). 2545-2567 (16 cites)

4. Details of the impact:

The central product of this research is the TRACK software package, which is freely available for download (http://www.nerc-essc.ac.uk/~kih/TRACK/Track.html). TRACK's impact has global reach because storm risks to people and property occur in many areas of the world, demonstrated by the uptake of the TRACK software, which has been downloaded by more than 40 institutes worldwide, including operational weather forecast centres, academic researchers, and "application users" (particularly in the insurance and weather forecasting sectors). Because it is freely available, we do not know the full extent of TRACK's usage and some applications we know of are in highly competitive commercial sectors and remain confidential. Specific examples of its use (in partnership with the Unit) are highlighted in more detail below, but on-going support requests[19] indicate more widespread use. The significance of the applications of TRACK is very high and it has contributed to novel quantitative analysis in the insurance sector as well as insights for policy-making and operational model development. TRACK's impact is subtle in some cases because TRACK is primarily an enabling tool (providing users with new ways to access and interpret storm data) rather than a specific scientific conclusion. TRACK has nevertheless made novel quantitative storm analyses possible in a wide variety of weather and climate datasets, including in-

house datasets owned by the end-users themselves.

The specific examples of TRACK usage discussed here fall into 3 categories: (1) use of TRACK to improve storm forecasts for the offshore industry; (2) use of TRACK to construct catalogues of storm events for use by the insurance industry in understanding risk and how it is changing; and (3) the use of TRACK to guide the improvement and use of climate simulation models.

BMT ARGOSS is a subsidiary of the BMT Group and is a leading maritime consultancy and weather forecast company, providing offshore forecasts to customers including oil and gas companies, transport companies, jetty operators, Liquid Natural Gas sites and dredgers. It has a strong collaboration with the Unit, where it funds a Professorship. Through this BMT learnt early of the Unit's work on storm forecasting and our conclusion (based on TRACK) that storms typically move more rapidly than estimated in weather forecast models.[18] As a result, since 2009 their in-house meteorologists have used TRACK to produce improved weather-forecast products for maritime emergency response and vessel routing.[24] For example, they now make improved estimates of storm arrival times at offshore oil rigs, thereby increasing the reliability of safety margins and decreasing the time that operations need to be shut-down due to extreme weather. A senior consultant and project manager states:[22] "*Customers require storm warnings alongside the regular weather forecasts. These dedicated forecasts cannot be produced reliably based on a single model, requiring more specialized tools. The TRACK software suite provides us with this capability. Currently the TRACK software is run operationally at BMT ARGOSS, 4 times per day. TRACK is becoming an essential part of our modelling infrastructure. It allows us to focus on the development of customer-specific products, and the development of a sustainable service*". A Maritime Meteorologist with BMT[23] notes that TRACK is "*particularly useful for our customers, such as dredging vessels or towing, that need to shelter for tropical cyclones and particularly for the high wind speed and wave height associated with it. We use the tracking software to identify storms at an early stage and advise our customers about wind speed and wave height. We use the ensembles to assess the most likely track of the cyclone and whether or not the wind speed and wave height are expected to reach certain thresholds*" and that "*We generate cyclone bulletins based on the ensembles. Particularly the expected ground track and estimated wind speed are of great importance to our customers such as vessels, rigs or ports*". TRACK is also influencing the future development of BMT's services: e.g., it is being used to generate statistics to improve typhoon warnings. Froude (NERC Knowledge Exchange fellow) and Hodges provided extensive support to BMT-ARGOSS over the last 5 years in applying TRACK with weather-forecast data.[19]

Storms are extremely important to the global insurance and reinsurance sectors.[20] In 2012, for example, storms produced global insured losses of $54bn and accounted for 75% of total insured losses.[21] Hence storms are a key risk for insurance exposure. Insurance companies need to quantify the risk posed by storms in order to assess exposure and set premiums, and this requires an understanding of the frequency and characteristics of storm events.

Willis is one of the "big three" global insurance brokers dealing with weather and climate catastrophe risk. Working in partnership with Willis since 2006 through the Willis Reinsurance Network, the Unit has used TRACK to derive a catalogue of tropical cyclones. Willis has used this in the development of its Tropical Cyclone Laboratory (TC Lab), a decision-making tool for brokers that combines observational and model data to identify robust evidence of evolving weather and climate risk, and acknowledge the invaluable input from the Unit.[25] The relationship between the Unit and Willis includes a Knowledge Transfer Partnership fellow (Dr J. Strachan), who was directly embedded with Willis' Natural Catastrophe Modelling and Product Development teams. Her work led to a broader understanding of the effects of climate variability and change on extreme events within Willis and, in particular, the need for robust long-term catalogues of tropical storm events to better assess present and future insurance risk.

TRACK has also been instrumental in the production of the Extreme Wind Storm (XWS) catalogue in collaboration with the Met. Office, Exeter University and Willis.[26] This catalogue of historical extratropical wind storms, including footprints of their damaging winds, has recently been made freely available but has been designed for use in the insurance industry in particular. The impact of the catalogue itself will be considerable but has yet to happen; however, the collaboration to develop it demonstrates how the application of TRACK is changing planning in the insurance industry. For example, in a study made possible only by the TRACK software, staff of Willis and Exeter University have studied the implications of clustering of windstorms for the insurance industry and discuss the scale of the associated losses.[27] A Willis briefing document notes "*These*

results will be of interest to insurers and reinsurers focussed on more accurate, actuarially-sound risk management of European windstorms, particularly those with spatially-extended portfolios and exposure in NW Europe". [28]

Risk Management Solutions (RMS) is one of 3 major international catastrophe modelling companies providing services to insurance and reinsurance companies. RMS use TRACK to analyse storms simulated by their in-house climate modelling and historical datasets. The storm tracks are used with their proprietary catastrophe model in their wind-storm risk assessment model which is widely used in the insurance sector within the UK and internationally.[34] The Unit is also currently working with the global insurance company, **Hiscox**, to improve understanding of their exposure to Atlantic hurricane risks. They have supported MSc and PhD projects in the Unit on the applications of TRACK .[29]

The **UK Met Office** runs one of the world's leading climate models, which has developed over time from the late 1980s to the current generation HadGEM2 family of models. The models have featured in all assessments of the Intergovernmental Panel on Climate Change (IPCC), are used to support policy advice provided by the Met Office to the UK government, and provided the basis for the climate scenarios (UKCIP98, UKCIP02 and UKCP09) used in the vast majority of assessments of the impacts of climate change in the UK. Many research projects and activities have supported the development over time of the Met Office climate model, and TRACK has played a part in this development.[30] The Met Office use the TRACK software and analysis package to assess the ability of models to reproduce storm characteristics, such as their track, frequency and intensity[31,32], and to show that increasing the spatial resolution of the climate model led to considerably improved representation of storms. HadGEM2 runs at double the spatial resolution and the use of TRACK provided further support for improving resolution.[32] The Met Office also use TRACK with their model simulations of future climate to assess potential changes in storm characteristics in targeted regional studies.[33] A testimonial letter[30] from the Met Office's Manager of global high resolution modelling list the many uses that they make of TRACK and concludes *"Overall, TRACK is a very important component of our model assessment and development suite"*

Background information

19. Details available upon request
20. NERC commissioned report by DTZ, High Resolution Climate Modelling and the Reinsurance Industry http://www.nerc.ac.uk/business/casestudies/documents/climate-reinsurance-report.pdf
21. Swiss Re (2013), Natural Catastrophes and Man-Made Disasters in 2012 http://bit.ly/16UllkX

5. Sources to corroborate the impact:

22. Testimonial letter from Project Manager for Meteorology and Senior Consultant Meteorology & Oceanography, BMT-ARGOSS. Available upon request
23. Testimonial letter a Maritime meteorologist at BMT-ARGOSS. Available upon request
24. The uses and importance of BMT's storm warning and tracking facility which employs the Unit's TRACK algorithm[22] is stressed on the BMT website http://bit.ly/17yPs21
25. Testimonial letter from Head of Proprietary Modelling, Executive Director Global Analytics & Willis Research Network, Willis Group. Available upon request
26. Willis Research Network. XWS catalogue published 4/9/2013 (available for internal use before then) http://bit.ly/17DhUxx (Follow **"**Ext. Link" and then "References" links to see use of TRACK)
27. R. Vitolo et al. (2009) Serial clustering of intense European storms, Met. Zeitschrift, 18 (4) 411-424. doi: 10.1127/0941-2948/2009/0393. This study by staff from Willis and Exeter University is made possible by the TRACK software (search for "Hodges")
28. Willis Research Network, briefing document http://bit.ly/1aQ3Xep (cites [26] that uses TRACK)
29. Testimonial letter from Non-Marine Treaty Underwriter, Hiscox, London. Available upon request
30. Testimonial letter from Manager of global high resolution modelling, the Met Office. Available upon request
31. C.Z. Greeves et al. (2007) Representation of Northern Hemisphere winter storm tracks in climate models, *Clim. Dyn*., 28, 683. doi: 10.1007/s00382-006-0205-x (search for "Hodges")
32. G.M. Martin et al. (2011) The HadGEM2 family of Met Office Unified Model climate configurations, *Geosci. Model Dev*., 4, 723, doi:10.5194/gmd-4-723-2011 (search for "Hodges")
33. R. McDonald (2011) Understanding the impact of climate change on northern hemisphere extra-tropical cyclones. *Clim. Dyn*. 37,1399. doi: 10.1007/s00382-010-0916-x (search for "Hodges")
34. Details of Unit's support for the development of this capability are available upon request