CSIRO PUBLISHING
Foreword
www.publish.csiro.au/journals/ijwf
International Journal of Wildland Fire **2010**, *19*, 991–995

Wildfires in boreal ecosystems: past, present and some emerging trends

Martin P. Girardin[A,E], *Adam A. Ali*[B,C] *and Christelle Hély*[D]

[A]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., PO Box 10380, Stn Sainte-Foy, Québec, QC, G1V 4C7, Canada.
[B]Centre de Bio-Archéologie et d'Écologie (UMR 5059 CNRS), Université Montpellier 2, 163 rue Auguste-Broussonet, Montpellier, F-34090, France.
[C]Chaire industrielle en aménagement forestier durable (NSERC-UQAT-UQAM), CP 8888, Succ. Centre-ville, Montréal, QC, H3C 3P8, Canada.
[D]Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, Université Aix-Marseille III, CNRS UMR 6635, Europôle de l'Arbois, BP 80, Aix-en-Provence cedex 4, F-13545, France.
[E]Corresponding author. Email: martin.girardin@nrcan.gc.ca

Abstract. With the emergence of a new forest management paradigm based on the emulation of natural disturbance regimes, interest in fire-related studies has increased in the boreal forest management community. A key issue in this regard is the improvement of our understanding of the variability in past disturbances and its linkages with climate and ecosystems. The surge in research activity has further been exacerbated by the increasing awareness of climate change, which has already exposed boreal forests to greater fire risk in recent decades. It is anticipated that further warming and drying will further enhance fire frequency and area burned in many boreal forests. Better predictions of future fire activity will contribute to better long-term forest planning in managed boreal forests. The 12 papers presented in this special issue exemplify this increased research activity by bringing together studies from diverse disciplines and presenting the latest advances regarding methodological approaches for reconstruction and modelling of past, present and future fire activity. Here we aim to summarise, evaluate and set into context some of the new insights arising from these studies and also to discuss some considerations to be taken into account in future research activities.

Additional keywords: biomass burning, carbon emissions, charcoal analysis, fire history, palaeoecology, simulation model.

Introduction and background

Fire is a primary natural process in circumboreal forests from Alaska to Russia, organising physical and biological attributes of the forests, shaping their landscape diversity, and influencing their biogeochemical cycles. Despite the increasing importance of human activity as a source of fire ignition (Marlon *et al.* 2008), dry forest fuels and winds are recognised as the major contributors to large stand-replacing fires in these forests. As opposed to arid, sparsely vegetated ecosystems, fuel is generally not considered a limiting factor for fire spread in boreal forests (Johnson and Larsen 1991). Human-caused climate change has already exposed boreal forests to greater fire risk in recent decades (Gillett *et al.* 2004) and it is anticipated that further warming and drying over the 21st century will enhance fire frequency and area burned in many boreal forests, with severe environmental and economic consequences (Flannigan *et al.* 2009). It is therefore not surprising to see an increasing interest surrounding climate change issues in fire science that is directly reflected in peer-reviewed literature (Fig. 1).

In this era of climate change, understanding past and predicting future fire activity are scientific challenges that are central to the development of effective forest management policies aiming to mitigate greenhouse gas emissions and increase adaptation capacity in response to climate change. Interest in fire-related studies has notably increased in the management community with the emergence of a new forest management paradigm based on the emulation of natural disturbance regimes (e.g. Gauthier *et al.* 2009). In this framework, a key issue is the improvement of our understanding of the natural variability of past disturbances and its linkages with climate and ecosystem dynamics. Additionally, it is becoming increasingly clear that direct responses of forests to climate change (e.g. through moisture availability and lengthening of the growing season) can be altered by a second-order impact via changes in the age class distribution of forest landscapes that results directly from changes in fire activity (e.g. Kurz *et al.* 2008; Goulden *et al.* 2010). Better predictions of future fire activity at mid-term timescales can contribute to better long-term forest planning in managed boreal forests and better estimation of future carbon balances.

That being said, such objectives remain difficult to achieve. Uncertainties about future fire activity can be superimposed on

© IAWF 2010
10.1071/WFv19n8_FO 1049-8991/10/080991

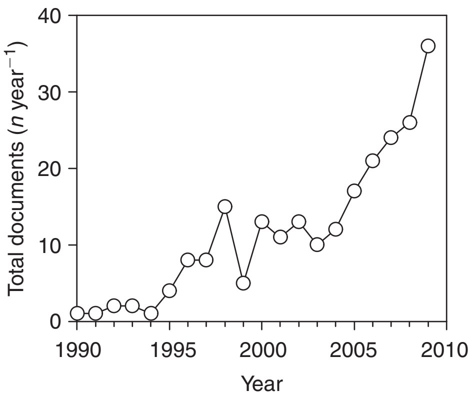

Fig. 1. Annual number of papers published in peer-reviewed scientific journals from 1990 to 2009 containing the words 'fire', 'boreal' and 'climate change' in the article's title, abstract or keywords ($n = 246$ documents). Data from Scopus (Elsevier, retrieved 29 September 2010).

the short time period covered by existing meteorological data and fire statistics, from which a historical range of variability can be determined. For instance, it is methodologically impossible to deduce an accurate fire return interval statistic with a single dataset spanning only the last 50 years or so. As demonstrated by Whitlock *et al.* (2010*a*), an estimated mean fire return interval might be accurate, but it will be associated with large confidence intervals. Fire activity in many boreal regions is also tremendously time-dependent (Girardin *et al.* 2006), such that a single record covering the last 50 years or so cannot provide information on the full range of fire activity variability a given forest experienced and has adapted to. This factor is increasingly important when it comes to determining the resilience of boreal forests to changes in climate and disturbance regimes. This factor also makes the contribution of changing fire activity to future vegetation changes on a given territory highly uncertain because the life-span of a given forest stand is much longer than historical records of fire activity.

The 'Wildfires in Boreal Ecosystems' conference was organised to gather fire researchers and managers for an exchange focussed on the latest methodological approaches for reconstruction and modelling of past, present and future fire activity. It was held on 14–17 March 2009, at the biological station of the Université du Québec en Abitibi-Temiscamingue, Québec (Canada), with 31 presentations attended by 48 participants. The 12 papers gathered in the present *IJWF* issue derive from those presentations. The conference was structured around three main topics. The first series of papers focuses primarily on the reconstruction of past fire activity (the last 11 000 years or so). The subsequent papers focus on contemporary fire activity (the last 50 years or so), and the final two report on future fire activity.

New insights into past fire activity

In the past several decades, significant progress has been made in characterising variability of past fire activity in circumboreal forests from 'proxy' records, that is, indirect observations. These advances include reconstructions from fire-scarred trees, stand establishment records, tree rings, charcoal particles preserved in lake sediments, peat-bog and soil deposits, and ammonium concentration [NH^{4+}] in ice cores (see Whitlock *et al.* 2010*b* for an overview of paleofire research). The first four papers of this issue (Bradshaw *et al.* 2010; Bremond *et al.* 2010; Carcaillet *et al.* 2010; Higuera *et al.* 2010) report on analyses of sedimentary charcoals preserved in lake sediments, whereas the last paper on this topic (Niklasson *et al.* 2010) is based on dendrochronological analysis.

Charcoal particles provide key information on climate–fire–vegetation interactions and human pressures on terrestrial ecosystems for periods encompassing several thousand years. However, their analysis remains a difficult task owing to the complexity of the process of lake sediment and charcoal accumulations. Nevertheless, this science is leading the way towards rapid development of new techniques for improved and more robust fire reconstructions. The work by Higuera *et al.* (2010) notably provides a historical and critical overview of the statistical techniques used for filtering out fire signals from the background noise in sedimentary charcoal records, and concludes with sound recommendations for follow-up studies. The study by Bremond *et al.* (2010) addresses the question of carbon emissions from fires and proposes an original method for the estimation of such quantity based on sedimentary charcoal records, with an application to eastern boreal Canada. Biomass combustion is one of the most important elements in global carbon flux processes, and yet very few attempts have been made to estimate the past rate of carbon releases into the atmosphere through paleo-biomass burning (Carcaillet *et al.* 2002).

The impact of fire-frequency change on plant diversity and community structure in boreal forests remains poorly understood. Similarly, theories concerning biogeography ecological functioning, biological diversity, and relationships to disturbance and stability remain to be tested on particular system designs, for instance on island–mainland systems (Bergeron 1991). The study by Carcaillet *et al.* (2010) examines the relationships between changes in mean fire interval and vegetation inferred from pollen datasets through the use of multivariate statistics and ecological indices applied to eastern Canada. The authors found no major shifts in species assemblages, but they did find significant changes in fire return intervals. They conclude that eastern North American boreal forests may be resilient to changes in fire activity.

In the study by Bradshaw *et al.* (2010), fire activity of temperate and hemiboreal forest zones from southern Scandinavia is documented for the last 3500 years. The study reports that fire activity has been significantly greater in the hemiboreal zone during the last 3500 years, suggesting that fuel type has had a significant impact on its spatial occurrence. As for vegetation itself, the study pinpoints that its dynamics has mostly been modulated by agro-pastoral practices and climate modifications; these two factors contributed to minimise the role of fire as a key ecological factor.

Comparative analysis of fire history in island–mainland systems is an important issue for understanding natural disturbance regimes, especially in areas with a long history of forest management and active fire suppression on mainland locations. Using dendrochronological techniques, the study by Niklasson *et al.* (2010) provides an example of such study design with a reconstruction of fire history for the past 400 years in southeastern Sweden. The study reports a dramatic shift in fire activity taking place at the end of the 19th century. Fire suppression (via a reduction in human-related ignitions) likely was behind the major decline in fire activity during the 1800s, more so than the direct effect from climate change.

Contemporary fire statistics and spatial patterns in burning

Contemporary fire statistics are widely used for understanding the occurrence and distribution of fires. These statistics are also used for calibrating fire models employed in forecasts and reconstructions of fire regimes, and for studying the role of historical fire disturbance in regional and global carbon dynamics. Statistics most often used are the total number of fires, area burned, and ignition sources. The origins of spatial and temporal variations in fire activity in the boreal forest remain uncertain. The debate in peer-reviewed scientific literature on fire suppression effectiveness in the boreal forest (see review by Martell and Sun 2008) is a straightforward example of the difficulties inherent to the interpretation of a complex system. Quantitative knowledge on spatial and temporal patterns could lead to the development of fire response and suppression strategies appropriate to specific regions within the boreal forest, provided that suitable data are available. The next five papers of this issue focus specifically on our understanding of spatial patterns in burning.

The study by Wang and Anderson (2010) introduces the use of *K*-function and kernel estimation for comparing the spatial characteristics of lightning- and human-caused fires. Their method applied to Alberta's boreal forest highlights the existence of an interaction between space and time, and confirms previous observations about the spatial distribution of lightning- and human-caused fires in this province. The study by Drobyshev *et al.* (2010) examines the differences in fire regime in an island-mainland system of eastern Canada, and evaluates possible sources for these differences. They report that drought-related weather conditions are more frequent and more intense on islands than on the mainland, and lighting strike frequency is higher within the lake perimeter, as compared with the mainland. Both factors contribute to explaining why fire activity is higher on lake islands.

It has long been thought that site conditions could affect fire potential. The work by Mansuy *et al.* (2010) reports on an analysis of the effects of environmental characteristics on spatial variations in fire activity through the use of a new classification of surficial deposit-drainage (SDD). Their SSD classification is a combination of surficial deposits grouped in terms of their texture, stoniness, thickness and morphology to derive site dryness potential. Although the fire cycle appears to be predominantly under climatic control, the authors indicate that the effect of differential SDD drying potential is stronger in regions where climate is humid and fire cycle is long.

Superimposed on spatial variability created by such substrate conditions is the influence of vegetation and fuel. The study by Hély *et al.* (2010) reports on a long-range fire growth model system, the Prescribed Fire Analysis System (PFAS) based upon meteorology, which is used to analyse the effect of landscape composition on fire size in Canadian boreal forests. The authors' results point to the effect of weather on fire propagation as the most important factor influencing fire size, followed by forest fuel composition and, to a lesser extent, by weather conditions directly related to fire ignition. Forest mosaics dominated by shade-intolerant hardwood species (as a result of short-term fire cycles) are subject to small fires, whereas mosaics dominated by shade-tolerant species and associated with intermediate- to long-term fire cycles experienced significantly larger fires. That being said, large fires never burned the all available fuel but left a proportion of residual habitats, regardless of the physiographic unit. Madoui *et al.* (2010) document this spatial structure and its drivers with the use of classified Landsat satellite images and suggest that the local and regional physiographic conditions strongly influence the creation of residual habitats in forest burns.

Future fire activity and some considerations for future research

Climate change will affect fire activity in boreal ecosystems. The current challenge is to provide key data and state-of-the-art fire models that will allow researchers and managers to draw realistic pictures of future fire status and the consequences on ecosystem functioning, while taking uncertainties into account. In this regard, the use of global circulation models has been steadily increasing over the past decades to obtain variables upon which predictions of future fire activity have been made (see review by Flannigan *et al.* 2009). Predictions have been obtained using empirical modelling approaches (e.g. empirical equations integrating precipitation and temperature variables), process-based approaches (e.g. models applying ecological concepts to fire behaviour coupled with fire weather indices), and combinations of both (empirical equations integrating fire weather indices). Each model approach has strengths and weaknesses, but all are affected by the same uncertainties associated with future atmospheric CO_2 emissions, population growth, land-use changes, etc.

Bergeron *et al.* (2010) use the hybrid approach on an ensemble mean of 19 global climate model experiments to predict future fire activity in eastern boreal Canada. Using a synthesis of charcoal sedimentary data from three kettle lakes in their targeted region, the authors further assess the risk of seeing future fire activity exceed the historical range of variability. Their simulations show an unequivocal increase in fire risk and area burned by the end of the 21st century compared with today. Nevertheless, the authors find the predicted future burn rate to be below the historical upper bound assessed from charcoal sedimentary data. Of course, this study design is not without uncertainties. In this issue's last paper, Metsaranta (2010) examines how interannual variability in area burned and short time-series of observations affect the ability to detect a climate change effect in fire predictions. He reports that numerical details are sensitive to several assumptions, including the area of forest, the probability distribution used to model annual area burned, and the maximum area that can burn in one year. As objective selection criteria are largely missing in fire prediction studies, follow-up studies should consider an approach based on the ensemble prediction system used for operational weather forecasting (Zhu 2005). This ensemble mean should be drawn from thousands of runs, and each run would be obtained from particular settings of the calibration parameters, randomisation of the samples used for calibration (e.g. years), different model and greenhouse gas emissions scenarios, etc. (e.g. Neukom *et al.* 2010). This approach could offer a robust forecast for the future uncertainty that could be directly implemented in some aspects of sustainable forest management. The work by Bergeron *et al.* (2010), by using multiple climate models, is an initial step in this direction.

Conclusion

The papers in this issue point to the complexity of the processes leading to spatial and temporal patterns of fires. Weather related to propagation and to fire ignition, surficial deposit-drainage and forest fuel composition influences fire size, intervals and patchiness (Drobyshev *et al.* 2010; Hély *et al.* 2010; Madoui *et al.* 2010; Mansuy *et al.* 2010). The long-term perspective from the paleoecological studies presented here show that the boreal forest may experience important changes in fire activity without experiencing major transformation in its vegetation. These forests therefore appear, at some level, to be resilient to changes in fire activity (Carcaillet *et al.* 2010). Nonetheless, even though fire is a long-term intrinsic property of the boreal forest (Bremond *et al.* 2010; Carcaillet *et al.* 2010; Higuera *et al.* 2010), its occurrence is increasingly linked with human activities (Marlon *et al.* 2008; Bradshaw *et al.* 2010; Niklasson *et al.* 2010; Wang and Anderson 2010). This influence has up until now been direct, via ignition, but the indirect influence through human-induced climate change is becoming worrisome (Flannigan *et al.* 2009; Bergeron *et al.* 2010; Metsaranta 2010). Furthermore, the cumulative impacts of fire and clear-cutting or other low-retention types of harvesting are becoming increasingly preoccupying when faced with the potential for these forests to exceed ecological thresholds (Cyr *et al.* 2009; Bergeron *et al.* 2010). The 'Wildfires in Boreal Ecosystems' conference and this special issue illustrate how effective collaborations can be developed amongst researchers of Eurasia and North America sharing similar interests. Hopefully, the papers presented here will prompt further ideas requiring collaborative efforts from cross-disciplines in biological and environmental sciences for a better understanding of fire behaviour.

Acknowledgements

The Conference Program Committee (Adam A. Ali, Martin P. Girardin, Hugo Asselin, Yves Bergeron, Christopher Carcaillet, Mike D. Flannigan, Sylvie Gauthier, Christelle Hély-Alleaume) oversaw the technical content of the conference and provided guidance to sponsoring agencies, associations and universities. The Committee thanks the Centre d'étude de la forêt (CEF), the Chaire industrielle CRSNG-UQAT-UQAM en aménagement durable des forêts, the Forêt d'enseignement et de recherche du Lac Duparquet, the Université du Québec en Abitibi-Témiscamingue, Natural Resources Canada, the ministère des Ressources naturelles et de la Faune du Québec, the Société de protection des forêts contre le feu (Québec), the ministère des Relations internationales du Québec, the Consulat général de France à Québec, and the Centre National de la Recherche Scientifique (CNRS, France) for making this conference possible. The Committee also thanks Raynald Julien, Daniel Lesieur and Marie-Hélène Longpré for their help with logistics.

References

Bergeron Y (1991) The influence of island and mainland lakeshore landscapes on boreal forest fire regimes. *Ecology* **72**, 1980–1992. doi:10.2307/1941553

Bergeron Y, Cyr D, Girardin MP, Carcaillet C (2010) Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. *International Journal of Wildland Fire* **19**, 1127–1139. doi:10.1071/WF09092

Bradshaw RHW, Lindbladh M, Hannon GE (2010) The role of fire in southern Scandinavian forests during the late Holocene. *International Journal of Wildland Fire* **19**, 1040–1049. doi:10.1071/WF09108

Bremond L, Carcaillet C, Favier C, Ali AA, Paitre C, Bégin Y, Bergeron Y, Richard PJH (2010) Effects of vegetation zones and climatic changes on fire-induced atmospheric carbon emissions: a model based on paleo-data. *International Journal of Wildland Fire* **19**, 1015–1025. doi:10.1071/WF09096

Carcaillet C, Almquist H, Asnong H, Bradshaw RHW, Carrión JS, Gaillard M-J, Gajewski K, Haas JN, Haberle SG, Hadorn P, Müller SD, Richard PJH, Richoz I, Rösch M, Sánchez Goñi MF, von Stedingk H, Stevenson AC, Talon B, Tardy C, Tinner W, Tryterud E, Wick L, Willis KJ (2002) Holocene biomass burning and global dynamics of the carbon cycle. *Chemosphere* **49**, 845–863. doi:10.1016/S0045-6535(02)00385-5

Carcaillet C, Richard PJH, Bergeron Y, Fréchette B, Ali AA (2010) Resilience of the boreal forest in response to Holocene fire-frequency changes assessed by pollen diversity and population dynamics. *International Journal of Wildland Fire* **19**, 1026–1039. doi:10.1071/WF09097

Cyr D, Gauthier S, Bergeron Y, Carcaillet C (2009) Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Frontiers in Ecology and the Environment* **7**, 519–524. doi:10.1890/080088

Drobyshev I, Flannigan MD, Bergeron Y, Girardin MP, Suran B (2010) Variation in local weather explains differences in fire regimes within a Québec south-eastern boreal forest landscape. *International Journal of Wildland Fire* **19**, 1073–1082. doi:10.1071/WF09101

Flannigan MD, Krawchuk MA, de Groot WJ, Wotton BM, Gowman LM (2009) Implications of changing climate for global wildland fire. *International Journal of Wildland Fire* **18**, 483–507. doi:10.1071/WF08187

Gauthier S, Vaillancourt M-A, Leduc A, De Grandpré L, Kneeshaw DD, Morin H, Drapeau P, Bergeron Y (2009) 'Ecosystem Management in the Boreal Forest.' (Les Presses de l'Université du Québec: Montreal)

Gillett NP, Weaver AJ, Zwiers FW, Flannigan MD (2004) Detecting the effect of climate change on Canadian forest fires. *Geophysical Research Letters* **31**, L18211. doi:10.1029/2004GL020876

Girardin MP, Bergeron Y, Tardif JC, Gauthier S, Flannigan MD, Mudelsee M (2006) A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada. *International Journal of Wildland Fire* **15**, 375–388. doi:10.1071/WF05065

Goulden ML, McMillan AMS, Winston GC, Rocha AV, Manies KL, Harden JW, Bond-Lamberty BP (2010) Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. *Global Change Biology* [Published online before print in 2010]. doi:10.1111/J.1365-2486.2010.02274.X

Hély C, Fortin M-J, Anderson KR, Bergeron Y (2010) Landscape composition influences local pattern of fire size in the eastern Canadian boreal forest. *International Journal of Wildland Fire* **19**, 1099–1109. doi:10.1071/WF09112

Higuera PE, Gavin DG, Bartlein PJ, Hallett DJ (2010) Peak detection in sediment-charcoal records: impacts of alternative data analysis methods on fire-history interpretations. *International Journal of Wildland Fire* **19**, 996–1014. doi:10.1071/WF09134

Johnson EA, Larsen CPS (1991) Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology* **72**, 194–201. doi:10.2307/1938914

Kurz WA, Stinson G, Rampley GJ, Dymond CC, Neilson ET (2008) Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences of the United States of America* **105**, 1551–1555. doi:10.1073/PNAS.0708133105

Madoui A, Leduc A, Gauthier S, Bergeron Y (2010) Spatial pattern analyses of post-fire residual stands in the black spruce boreal forest of western Quebec. *International Journal of Wildland Fire* **19**, 1110–1126. doi:10.1071/WF10049

Mansuy N, Gauthier S, Robitaille A, Bergeron Y (2010) The effects of surficial deposit–drainage combinations on spatial variations of fire cycles in the boreal forest of eastern Canada. *International Journal of Wildland Fire* **19**, 1083–1098. doi:10.1071/WF09144

Marlon JR, Bartlein PJ, Carcaillet C, Gavin DG, Harrison SP, Higuera PE, Joos F, Power MJ, Prentice IC (2008) Climate and human influences on global biomass burning over the past two millennia. *Nature Geoscience* **1**, 697–702. doi:10.1038/NGEO313

Martell DL, Sun H (2008) The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario. *Canadian Journal of Forest Research* **38**, 1547–1563. doi:10.1139/X07-210

Metsaranta JM (2010) Potentially limited detectability of short-term changes in boreal fire regimes: a simulation study. *International Journal of Wildland Fire* **19**, 1140–1146. doi:10.1071/WF10037

Neukom R, Luterbacher J, Villalba R, Küttel M, Frank D, Jones PD, Grosjean M, Esper J, Lopez L, Wanner H (2010) Multi-centennial summer and winter precipitation variability in southern South America. *Geophysical Research Letters* **37**, L14708. doi:10.1029/2010GL043680

Niklasson M, Drobyshev I, Zielonka T (2010) A 400-year history of fires on lake islands in south-east Sweden. *International Journal of Wildland Fire* **19**, 1050–1058. doi:10.1071/WF09117

Wang Y, Anderson KR (2010) An evaluation of spatial and temporal patterns of lightning- and human-caused forest fires in Alberta, Canada, 1980–2007. *International Journal of Wildland Fire* **19**, 1059–1072. doi:10.1071/WF09085

Whitlock C, Higuera PE, McWethy DB, Briles CE (2010*a*) Paleoecological perspectives on fire ecology: revisiting the fire regime concept. *Open Ecology Journal* **3**, 6–23. doi:10.2174/1874213001003020006

Whitlock C, Tinner W, Newman L, Kiefer T (2010*b*) Fire in the earth system: a paleoperspective. *PAGES Newsletter* **18**. Available at http://www.pages-igbp.org/cgi-bin/WebObjects/products.woa/wa/product?id=448 [Verified 15 November 2010]

Zhu Y (2005) Ensemble forecast: a new approach to uncertainty and predictability. *Advances in Atmospheric Sciences* **22**, 781–788. doi:10.1007/BF02918678