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GEOLOGICAL SURVEY OF CANADA
BULLETIN 421

SENSITIVITY OF EOLIAN PROCESSES TO CLIMATE CHANGE IN CANADA

S.A. Wolfe and W.G. Nickling

1997

B. 421
$14.30

Natural Resources Canada Ressources naturelles Canada

Canada

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SENSITIVITY OF EOLIAN PROCESSES TO CLIMATE CHANGE IN CANADA

Impact of global change on geological processes in Canada

S.A. Wolfe and W.G. Nickling

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Catalogue No. M42-421E
ISBN 0-660-16901-0

Available in Canada from
Geological Survey of Canada offices:

601 Booth Street
Ottawa, Ontario K1A 0E8

3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

101-605 Robson Street
Vancouver, B.C.
V6B 1R8

or from

Canada Communication Group – Publishing
Ottawa, Ontario K1A 0S9

A deposit copy of this publication is also available for reference
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Cover illustration

Ranch buildings lying in path of an active sand dune, west-central Great Sand Hills. Note that the darker coloured strip which makes up the skyline is an area of stabilized dunes which was active during periods of drought such as those occurring in the 1930s. This and similar stabilized areas in Canada could once again be reactivated if the climate change which is predicted were to occur. GSC 1995-085

Price subject to change without notice

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Original manuscript submitted: 11-04-94
Final version approved for publication: 12-05-94

FOREWORD

Change is a welcomed or feared challenge. It is welcomed when the outcome is understood and expected to be good; it is feared when the outcome is unknown or expected to be bad. Global climate change is the most significant projected change currently facing humanity. Global climate change is a feared change because it involves many unknowns. What will be the rate and level of climate change? How will global climate change be "distributed" or impact on various regions? How will the complex earth ecosystems be effected? Most importantly, how will humanity cope?

One element of the global change picture, which falls within the mandate of the Geological Survey of Canada, is surface geological processes. Surface geological processes include the various forces which act to change the Earth's surface. The ones with which we are most familiar are water and wind. These act on the surface by eroding (removing) materials from one place and depositing them in another. Climate plays a major role in driving these processes and changes in climate will result in changes in their nature and intensity.

Through time we have gained knowledge which lets us predict what to expect from surface geological processes and hence to mitigate their harmful effects. For example, application of process knowledge has resulted in development of local practices such as planting shelter belts and strip farming to control soil erosion on individual fields, and in government initiatives such as removing land from cultivation to mitigate damage on a regional scale. If future global climate changes result in changes in natural process activities, then different mitigative measures will have to be developed. Developing and implementing new coping strategies requires research, planning, and time, hence, the sooner we can gather information on what to expect the better prepared we will be to take action when the changes occur.

The Geological Survey of Canada is preparing overview reports on the more common geological processes occurring in Canada. Each of these reports includes a map showing aerial distribution of process activity today and areas where this process is most sensitive to climate change. Each looks at how different factors control process activity, discusses the sensitivity of the process to climate change, and considers the impact of different aspects of the process on human activity. These are not intended as research documents which predict what might be expected in each part of the country but as warnings to draw attention to potential "hotspots" or areas where the process in question is likely to be most affected by global climate change. The hope is that this first step will foster and focus followup research which will determine potential impact more precisely and provide information for planning mitigative measures.

R.J. Fulton,
Co-ordinator

Impact of Global Climate Change on Geological Processes

AVANT-PROPOS

Le changement est un défi bienvenu ou redouté. Il est bienvenu lorsqu'on connaît bien les conséquences et qu'on les prévoient favorables; il est redouté lorsque les conséquences sont inconnues ou présumées nuisibles. Le changement climatique global est le changement prévu le plus significatif auquel doit actuellement faire face l'humanité. Le changement climatique global est un changement redouté étant donné qu'il comporte de nombreuses inconnues. À quel rythme et à quel niveau aura lieu le changement climatique? Comment le changement climatique global sera-t-il «distribué» ou quelles répercussions aura-t-il sur les diverses régions? Comment seront affectés les écosystèmes complexes de la Terre? Encore plus important, comment réagira l'humanité?

L'un des éléments du changement global relevant du mandat de la Commission géologique du Canada est lié aux processus géomorphologiques. Ces processus incluent les diverses forces qui agissent à la surface de la Terre. Celles qui nous sont les plus connues sont l'eau et le vent qui agissent à la surface en érodant (déplaçant) les matériaux à un endroit pour les transporter à un autre. Le climat joue une rôle important dans le déroulement de ces processus de sorte que les changements climatiques se traduiront par des changements dans leur nature et leur intensité.

Avec le temps, nous avons acquis des connaissances qui permettent de prédire les processus géomorphologiques et d'atténuer leurs effets néfastes. Par exemple, l'application des connaissances actuelles sur les processus ont permis d'élaborer des méthodes locales comme l'implantation de brise-vent et le recours à la culture en bandes alternantes pour contrer l'érosion des sols dans les champs et de mettre en oeuvre des projets gouvernementaux comme l'interruption de cultures pour diminuer les dommages à l'échelle régionale. Si les changements climatiques globaux dans l'avenir devaient modifier les processus naturels, il faudrait alors mettre au point différentes mesures pour restreindre leurs effets. L'élaboration et l'application de nouvelles stratégies de correction nécessitent des recherches, de la planification et du temps. C'est pourquoi en recueillant le plus rapidement possible des informations sur les prévisions, nous serons mieux préparés à réagir lorsque les changements surviendront.

La Commission géologique du Canada prépare actuellement des rapports sommaires sur les processus géologiques les plus courants observés au Canada. Chacun de ces rapports comprend une carte montrant la répartition spatiale des processus actuels et les zones où ces processus réagissent le plus au changement climatique. On y traite dans chacun des rapports de la façon dont les différents facteurs agissent sur les processus, de la sensibilité des processus au changement climatique et des répercussions des différents aspects des processus sur l'activité humaine. Ce ne sont pas des documents de recherche qui contiennent des prévisions sur les changements dans chaque région du pays; ils visent plutôt à attirer l'attention sur les «points chauds» ou les régions où les processus en question sont le plus susceptibles d'être affectés par le changement climatique global. Nous espérons que la première étape mettra l'accent sur un suivi des recherches qui permettra d'établir les répercussions potentielles de façon plus précise et fournira des informations utiles pour la planification de mesures correctrices.

R.J. Fulton
Coordonnateur

Répercussions du changement climatique global sur les processus géologiques

Preface

This bulletin, which is part of the Geological Survey of Canada's "Impact of Global Climate Change on Geological Processes", looks at the relationship between climate- and wind-related geological processes and discusses how predicted global climate change could result in modification of soil erosion and activity of sand dunes.

Information drawn from several sources was used to compile a map which rates the susceptibility of sand dune and agricultural areas of Canada to eolian processes caused by aspects of climatic change. This documents the first important step toward identifying the areas of Canada where wind erosion and related problems are most sensitive to global climate change. Critical regions are highlighted where studies must now be conducted to outline the probable local impact of global change and to develop the best coping mechanisms. Only through studies such as this which provide information on the possible impacts of global change can we begin to come to grips with the potential magnitude of the problem.

This report was prepared under the auspices of the Global Change Program of the Geological Survey of Canada with the partial support of the Canada Green Plan Fund.

M.D. Everell
Assistant Deputy Minister
Earth Sciences Sector

Préface

Le présent bulletin, qui fait partie des «Répercussions du changement climatique global sur les processus géologiques» de la Commission géologique du Canada, se penche sur le lien qui existe entre le climat et les processus géologiques liés à l'action du vent, traite de la façon dont le changement climatique global prévu pourrait modifier l'érosion des sols et l'activité des dunes de sable.

Des informations tirées de plusieurs sources ont été utilisées pour dresser une carte des zones de dunes de sable et des zones agricoles du Canada dans laquelle est évaluée leur sensibilité aux processus éoliens provoqués par le changement climatique. Il s'agit de la première étape importante d'un projet visant à identifier les régions du Canada où l'érosion éolienne et les problèmes de même nature sont les plus susceptibles de subir les effets du changement climatique global. Les régions cruciales où des études doivent être menées pour délimiter les répercussions locales probables du changement global et pour élaborer des mécanismes de correction sont mises en évidence. Seules les études approfondies comme celle-ci, qui renseigne sur les effets possibles du changement global, peuvent nous aider à évaluer l'ampleur possible du problème.

Ce rapport a été préparé sous les auspices du Programme des changements à l'échelle du globe de la Commission géologique du Canada avec l'appui partiel du Fonds du Plan vert du Canada.

M.D. Everell
Sous-ministre adjoint
Secteur des sciences de la Terre

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SENSITIVITY OF EOLIAN PROCESSES TO CLIMATE CHANGE IN CANADA

Abstract

A relatively good understanding exists of wind erosion and other eolian processes under present-day conditions, but increases in atmospheric CO_2 concentrations have raised concerns over the impact of global climate change. Anticipated climate change associated with increased CO_2 concentrations could alter existing ecoclimatic regions in Canada. This, in turn, is likely to affect the distribution and relative intensity of eolian and other geomorphic processes. With regards to the impact of climate change, the sensitivity of sand dunes may be viewed, in a simplified manner, as a function of vegetation cover and surface soil moisture conditions, while the risk of wind erosion of bare soils may be considered primarily a function of surface soil moisture conditions.

Under a doubling of atmospheric CO_2 scenario, sand dunes in the southern regions of Alberta and Saskatchewan would lie in an ecoclimatic region identified as semidesert, and hence would become even more sensitive. Similarly, dune areas of southwestern Ontario would become more sensitive (the potential for sand dune activity would increase). Under these same hypothetical conditions, the sensitivity of coastal and arctic sand dunes would probably be low. Similarly, the risk of wind erosion of bare agricultural soils would still be greatest and would increase in southern Saskatchewan and Alberta, and probably would also increase in southwestern Ontario and portions of the Maritimes. Changes in intensity of agriculture, together with modification of cropping and management practices could, however, be used to mitigate against these increased impacts.

Résumé

On connaît relativement bien les processus d'érosion éolienne et autres processus dus au vent dans les conditions actuelles, mais l'augmentation des concentrations de CO_2 dans l'atmosphère a créé des préoccupations sur les répercussions du changement climatique global. La modification prévue du climat causée par une augmentation des concentrations de CO_2 pourrait se répercuter sur les régions écoclimatiques actuelles du Canada en remaniant probablement la répartition et l'intensité relative des processus éoliens et autres processus géomorphologiques. En ce qui concerne les incidences du changement climatique, la sensibilité des dunes de sable peut être perçue, d'une façon simplifiée, comme fonction de la couverture végétale et de l'humidité des sols superficiels tandis que le risque d'érosion éolienne des sols nus peut être considéré principalement en fonction des conditions d'humidité des sols superficiels.

Si la concentration de CO_2 atmosphérique doublait, les dunes de sable dans les régions méridionales de l'Alberta et de la Saskatchewan s'étendraient dans une région écoclimatique qualifiée de semi-désert, et de ce fait deviendraient encore plus sensibles. Il en irait de même des zones dunaires du sud-ouest de l'Ontario où le potentiel d'activité dunaire s'accroîtrait. Dans ces même conditions hypothétiques, la sensibilité des dunes de sable dans les zones littorales et arctiques serait probablement faible. De plus, le risque d'érosion éolienne des sols agricoles nus demeurerait le plus élevé et il augmenterait dans le sud de la Saskatchewan et de l'Alberta ainsi que probablement dans le sud-ouest de l'Ontario et dans certaines portions des Maritimes. Pour réduire ces répercussions, cependant, on pourrait modifier l'intensité de l'agriculture, tout comme les méthodes de culture et de gestion.

SUMMARY

In Canada, the limit of ecoclimatic regions could be changed by climate modifications induced by increased concentrations of carbon dioxide (CO_2) and other gases in the atmosphere (Fig. 1 [in pocket], insets A and B). The work of Rizzo and Wiken (1992) suggests that changes in precipitation and temperature caused by a doubling of the CO_2 within the next century will result in: 1) current grassland regions of southern Alberta and Saskatchewan becoming semidesert; 2) major increases in the area of grasslands, cool temperate, and moderate ecoclimatic regions; and 3) decreases in the area of boreal and arctic ecoregions. The shifting of boundaries of ecoclimatic regions will result in changes in nature and intensity of the geological processes which are active in these areas. Eolian processes (wind erosion of soil, transport of sand, construction of sand dunes, etc.) are one of the geological activities which will be affected. The distribution and intensity of eolian processes depends largely on the vegetation cover which can provide protection against wind erosion. In addition, the wind erosion susceptibility of bare soils is affected by surface soil moisture conditions so that changes in the amount and timing of precipitation coupled with alterations in temperature regimes will influence eolian processes. Other changes influencing eolian processes may include the nature and distribution of wind forces controlling the potential for sediment transport; lake and sea level changes affecting sediment supply for coastal dunes; river discharges influencing sediment supply; and changes to agricultural activity and practices driven by climatic conditions.

Given these complexities, a detailed assessment of the potential change in magnitude and distribution of eolian processes in Canada is not possible. However, a simplified assessment of the sensitivity of eolian processes to climate change may be made on the basis of the predicted changes in ecoclimatic regions. This sensitivity represents the predicted potential for increased movement or reactivation of sand dunes and increased erosion of bare, unprotected soils in response to climate change. This assessment takes into account changes in vegetation abundance and surface soil moisture conditions as indicated by predicted shifts in ecoclimatic regions. The sensitivity of sand dunes to climate change is considered low in regions where predicted changes in ecoclimatic regions result in vegetation cover or moisture conditions sufficient to suppress erosion. In agricultural areas, the level of wind erosion risk depends largely on agricultural practices so it is possible that by making changes in the nature and intensity of cropping or in soil management techniques the effects of increased sensitivity due to climate change could be held in check. As soil moisture decreases, however, it will become increasingly difficult and more expensive to mitigate against wind erosion. For the purposes of this report, the level of wind erosion risk is taken as that for bare unprotected soil and no assumptions are made about vegetation cover or agricultural practices. The sensitivity of the bare unprotected mineral soil to wind erosion is considered to be primarily a function of soil texture, wind regime,

SOMMAIRE

Au Canada, la limite des régions écoclimatiques pourrait être déplacée par les modifications climatiques causées par une augmentation des concentrations de dioxyde de carbone (CO_2) et d'autres gaz atmosphériques (fig. 1 [en pochette], cartouches A et B). Les travaux de Rizzo et Wiken (1992) révèlent que les changements dans les précipitations et les températures causés par la multiplication par deux de la concentration de CO_2 au cours du prochain siècle se traduiront par : 1) la semi-désertification des régions de prairie du sud de l'Alberta et de la Saskatchewan; 2) un accroissement important de l'étendue des prairies, des régions écoclimatiques tempérées froides et modérées; et 3) une diminution de l'étendue des écorégions boréales et arctiques. Le déplacement des limites des régions écoclimatiques causera des changements dans la nature et l'intensité des processus géologiques qui sont actifs dans ces régions. Les processus éoliens (érosion éolienne du sol, transport du sable, construction de dunes de sable, etc.) seront parmi les activités géologiques à subir des modifications. La répartition et l'intensité des processus éoliens dépendent largement de la couverture végétale qui peut protéger le sol contre l'érosion éolienne. De plus, la susceptibilité à l'érosion éolienne des sols nus dépend des conditions d'humidité des sols superficiels de sorte que les changements observés dans la quantité et la chronologie des précipitations conjugués aux modifications des régimes de température influeront sur les processus éoliens. Parmi les autres changements influant sur les processus éoliens, mentionnons la nature et la distribution des forces éoliennes régissant le potentiel de transport des sédiments; les changements du niveau des lacs et de la mer qui ont un effet sur l'apport sédimentaire des dunes littorales; les débits fluviatiles se répercutant sur l'apport sédimentaire; et les modifications des activités et méthodes agricoles attribuables aux conditions climatiques.

À cause de ces complexités, il n'est pas possible d'évaluer en détail les modifications possibles de l'ampleur et de la distribution des processus éoliens au Canada. Cependant, en se basant sur les changements prévus dans les régions écoclimatiques, on peut évaluer de façon simplifiée la sensibilité des processus éoliens au changement climatique. Cette sensibilité représente le potentiel prévu du déplacement accru ou de la réactivation des dunes de sable et de l'érosion accrue des sols nus non protégés en réponse au changement climatique. Cette évaluation tient compte des changements observés dans l'abondance de la végétation et les conditions d'humidité des sols superficiels tels qu'indiqués par les déplacements prévues dans les régions écoclimatiques. La sensibilité des dunes de sable au changement climatique est considérée faible dans les régions où les changements prévus dans les régions écoclimatiques se traduisent par une couverture végétale ou des conditions d'humidité suffisantes pour supprimer l'érosion. Dans les régions agricoles, le degré de risque d'érosion éolienne dépend largement des méthodes agricoles de sorte qu'il est possible, en apportant des modifications à la nature et à l'intensité des cultures ou aux techniques de gestion des sols, de contrôler les effets d'une sensibilité accrue attribuable à un changement climatique. À mesure que l'humidité des sols diminue, cependant, il deviendra de plus en plus difficile et plus coûteux d'atténuer l'érosion éolienne. Aux fins du présent rapport, le degré de risque en matière d'érosion éolienne correspond à celui des sols nus non protégés et aucune hypothèse n'est formulée sur les couvertures végétales ou les méthodes agricoles. La sensibilité à l'érosion éolienne des sols minéraux nus non

and surface soil moisture conditions. In this report, sensitivity of wind erosion risk to climatic change is considered to be greatest in areas with the highest surface soil moisture deficit under present conditions. In addition to agricultural practices mitigating against wind erosion, other effects such as changes in sediment supply due to alterations in groundwater, lake, or river levels are not considered.

The sensitivity of dune areas in Canada to climate change is illustrated in Figure 1 (in pocket). This sensitivity is derived by superimposing the future ecoclimatic regions based on a doubling of atmosphere CO_2 (Rizzo and Wiken, 1989, 1992; see inset B) on to the distribution of sand dunes in Canada (David, 1977, 1989; McCann, 1975, 1990; McKenna Neuman, 1990a; Hales, 1993). Climatic sensitivity ranges from severe to low with the least sensitive regions predicted to have either sufficient vegetation cover or surface soil moisture conditions to inhibit regional eolian activity under a CO_2 doubling scenario. These "safe" regions include the arctic, subarctic, boreal, cool temperate, transitional grassland, and those regions that may change from boreal to moderate temperate under this scenario. This represents most dune areas in Canada, including those in British Columbia, Quebec, Newfoundland-Labrador, Yukon Territory, and Northwest Territories as well as the northern reaches of Alberta, Saskatchewan, Manitoba, and Ontario. Climatic sensitivity is interpreted as moderate where existing boreal regions may change to grassland and where cool temperate regions may change to moderate temperate and includes central Saskatchewan and some regions of Manitoba, Ontario, Quebec, and the Maritimes. High sensitivity is interpreted where grassland and moderate temperate regions remain "unchanged", as it is likely that these regions will become more arid and drought-prone rather than less so under a CO_2 doubling scenario. Severe sensitivity is interpreted where existing ecoclimatic regions change to semidesert. This area roughly corresponds to the presently arid region of Canada known as the Palliser Triangle (brown soil or short grass prairie region). Included in this region of severe sensitivity are the Great Sand Hills of Saskatchewan, as well as several smaller sand hills in Saskatchewan and Alberta. In Nova Scotia and Newfoundland, the change from boreal to moderate temperate ecoclimatic regions is unlikely to increase dune sensitivity.

Figure 1 also indicates the sensitivity of wind erosion risk of bare, unprotected mineral soils to climate change. The map was derived by overlaying inset B, the future ecoclimatic regions (Rizzo and Wiken, 1989,1992) on inset C, the present wind erosion risk of bare, unprotected mineral soils in Canada (Coote et al., 1982; Coote et al., 1987a, b; Coote and Padbury, 1987). Unlike dune sensitivity, however, the sensitivity of wind erosion risk is not a function of vegetation cover since the surface is considered bare. Instead, climatic sensitivity reflects potential changes in surface soil moisture availability, accompanying changes in the ecoclimatic regions. A sensitivity matrix table is included as part of Figure 1. The upper

protégés est surtout considérée comme fonction de la texture du sol, du régime éolien et des conditions d'humidité du sol superficiel. Dans le présent rapport, la sensibilité des sols à l'érosion éolienne attribuable au changement climatique est maximale dans les régions qui présentent, dans les conditions actuelles, le déficit le plus élevé en ce qui concerne les sols superficiels. En plus des méthodes agricoles permettant d'atténuer l'érosion éolienne, d'autres effets comme les changements de l'apport sédimentaire causés par les fluctuations des niveaux d'eau dans les nappes souterraines, les lacs et les cours d'eau ne sont pas pris en compte.

La sensibilité au changement climatique des zones dunaires au Canada est illustrée à la figure 1 (en pochette). Cette sensibilité est établie en superposant les régions écoclimatiques futures basées sur une double concentration du CO_2 atmosphérique (Rizzo et Wiken, 1989, 1992; voir cartouche B) sur la distribution des dunes de sable au Canada (David, 1977, 1989; McCann, 1975, 1990; McKenna Neuman, 1990a; Hales, 1993). La sensibilité climatique varie de forte à faible, les régions les moins sensibles étant celles recouvertes d'une couverture végétale suffisante ou bénéficiant de conditions d'humidité du sol suffisantes pour contrer l'activité éolienne régionale dans une situation de double concentration de CO_2. Ces régions «protégées» incluent les régions arctiques, subarctiques, boréales, tempérées froides, de prairie de transition et celles qui pourraient, selon ce scénario, passer de boréale à tempérée modérée. Cela représente la plupart des régions dunaires du Canada, notamment celles de la Colombie-Britannique, du Québec, de Terre-Neuve-Labrador, du Yukon et des Territoires du Nord-Ouest ainsi que les parties septentrionales de l'Alberta, de la Saskatchewan, du Manitoba et de l'Ontario. La sensibilité climatique est interprétée comme modérée là où les régions boréales actuelles peuvent se transformer en prairie et là où les régions tempérées froides peuvent se transformer en régions tempérées modérées, soit dans le centre de la Saskatchewan et dans certaines régions du Manitoba, de l'Ontario, du Québec et des Maritimes. Par sensibilité élevée, on entend les prairies et les régions tempérées modérées «non modifiées» étant donné que ces régions deviendront probablement plus arides et qu'elles seront plus sujettes à la sécheresse si la concentration de CO_2 doublait. On parle de forte sensibilité là où les régions écoclimatiques actuelles se transforment en semi-déserts. Cette région correspond à peu près à la région aride du Canada appelée «triangle de Palliser» (région de sol brun ou de prairie courte). On inclut dans cette région de forte sensibilité les Great Sand Hills de la Saskatchewan, ainsi que plusieurs plus petites collines de sable de la Saskatchewan et de l'Alberta. En Nouvelle-Écosse et à Terre-Neuve, la transformation de régions écoclimatiques boréales en tempérées modérées ne devrait pas accroître la sensibilité des dunes.

La figure 1 indique également la sensibilité à l'érosion éolienne des sols minéraux nus non protégés. La carte a été obtenue en superposant la cartouche B des futures régions écoclimatiques (Rizzo et Wiken, 1989, 1992) sur la cartouche C figurant le risque actuel à l'érosion éolienne des sols minéraux nus non protégés au Canada (Coote et al., 1982; Coote et al., 1987a, b; Coote et Padbury, 1987). Contrairement à la sensibilité des dunes, le risque de sensibilité à l'érosion éolienne ne dépend pas de la couverture végétale puisque la surface est considérée nue. La sensibilité climatique reflète plutôt les changements possibles de l'humidité disponible dans les sols superficiels qui accompagnent les modifications des régions écoclimatiques. Un tableau matriciel de la sensibilité est row of the matrix indicates regions of most severe wind erosion risk under existing climatic conditions while the bottom row indicates regions of lowest risk. The columns identify regions of climatic sensitivity based on the scenario of CO_2 doubling. The leftmost column indicates regions of severe climatic sensitivity while the rightmost column indicates regions of low sensitivity. Combined, the regions of most severe wind erosion risk and climatic sensitivity are identified by the top left corner of the matrix while the regions of lowest risk and sensitivity are identified by the bottom right corner of the matrix.

The sensitivity of wind erosion on agricultural soils to climate change in Canada parallels that of sand dune sensitivity. In general, the southern prairies are identified as the area of greatest sensitivity, decreasing in sensitivity northward. Southern Ontario and portions of the Maritimes, including Prince Edward Island are identified as being moderately sensitive, with some high sensitivity regions in the extreme southern portion of Ontario. Other regions of the Maritimes, northern Quebec, and Ontario, as well as northwestern Alberta and British Colombia, are identified as having a low sensitivity to climate change. In general, while a high proportion of agricultural land in Canada has a low present wind erosion risk, it is those areas which have the highest present risk which also tend to be in the most climatically sensitive regions.

The sensitivity of sand dunes and the wind erosion risk to climate change in Canada shown on this map is speculative, and is based on only one possible scenario of climate change resulting from a doubling of atmospheric CO_2 concentrations. In addition, the basis for the climatic sensitivity of eolian processes has been greatly simplified to consider primarily changes in surface soil moisture availability and vegetation cover. As a consequence, anomalous areas exist such as the Athabasca Sand Dunes of northern Saskatchewan and Alberta which are active today in a region of comparatively low climatic sensitivity. Nevertheless, these maps may be used to identify regions which are potentially at risk to enhanced eolian activity resulting from climate change in Canada. Regions identified as severely sensitive represent those potentially most prone to enhanced movement of active sand dunes and reactivation of stabilized dunes in addition to escalated wind erosion of bare, unprotected soils under the doubling of CO_2 scenario.

inclus dans la figure 1. La rangée supérieure de la matrice indique les régions présentant le risque le plus élevé d'érosion éolienne dans les conditions climatiques actuelles tandis que la rangée inférieure indique les régions où ce risque est le plus faible. Dans les colonnes, on énumère les régions de sensibilité climatique basées sur le scénario d'une double concentration de CO_2. La colonne d'extrême gauche indique les régions de forte sensibilité climatique tandis que la colonne d'extrême droite indique les régions de faible sensibilité. Les régions les plus susceptibles de subir une érosion éolienne et les régions les plus sensibles à un changement climatique sont identifiées par le coin supérieur gauche de la matrice tandis que les régions les moins susceptibles de l'être et les moins sensibles sont identifiées par le coin inférieur droit de la matrice.

La sensibilité à l'érosion éolienne des sols agricoles due au changement climatique au Canada correspond à la sensibilité des dunes de sable. En général, les prairies méridionales sont identifiées comme la région la plus sensible, la sensibilité s'atténuant vers le nord. Le sud de l'Ontario et des portions des Maritimes, incluant l'Île-du-Prince-Édouard, sont identifiées comme modérément sensibles, mais comportent certaines régions très sensibles dans l'extrême sud de l'Ontario. D'autres régions des Maritimes, le nord du Québec et de l'Ontario, ainsi que le nord-ouest de l'Alberta et de la Colombie-Britannique, sont identifiées comme faiblement sensibles au changement climatique. En général, même si une proportion élevée des terres agricoles au Canada présente actuellement un faible risque d'érosion éolienne, ce sont ces régions qui présentent le risque le plus élevé et qui ont également tendance à être les régions les plus sensibles sur le plan climatique.

La sensibilité des dunes de sable et le risque d'érosion éolienne dû à un changement climatique au Canada figurés sur cette carte sont hypothétiques; ils ne sont fondés que sur un scénario possible de changement climatique résultant d'une concentration double de CO_2 atmosphérique. De plus, la base de la sensibilité climatique des processus éoliens a été grandement simplifiée pour tenir compte principalement des changements de l'humidité disponible des sols superficiels et de la couverture végétale. Par conséquent, il existe des zones anomales comme les dunes de sable d'Athabasca dans le nord de la Saskatchewan et de l'Alberta qui sont actives aujourd'hui dans une région comparativement peu sensible au changement climatique. Néanmoins, ces cartes peuvent servir à identifier les régions où risque d'augmenter l'activité éolienne par suite d'un changement climatique au Canada. Les régions identifiées comme très sensibles représentent celles qui sont les plus susceptibles de subir un déplacement accru des dunes de sable actives et une réactivation des dunes stabilisées en plus d'une érosion éolienne amplifiée des sols nus non protégés si la concentration de CO_2 devait doubler.

INTRODUCTION

Eolian processes result from the interaction between the atmosphere and the Earth's surface. The nature of eolian activity depends on the availability of wind-transportable sediment together with numerous atmospheric and surface variables. Eolian processes remove materials from one location and deposit them in another, thus modifying the landscape and affecting human activities. Although eolian processes have typically been viewed as detrimental, fine grained wind deposited materials can improve the quality of soils by adding fine mineral material and nutrients. Similarly, wind deposited coastal dunes can protect nearshore regions from flooding.

Historically, wind erosion in Canada has intensified during periods of drought. During the "Dust Bowl" conditions of the 1930s and again in the late 1980s, deflation of agricultural soils and the frequency of dust storms increased in the prairie region of Canada (Wheaton and Arthur, 1989). Several studies suggest that the frequency and intensity of drought in Canada may be intensified by climate change brought about by an increase in atmospheric CO_2 concentrations (Smit, 1987; Stewart et al., 1987). Consequently, there will be an increased potential for wind erosion, especially on cultivated soils. Recent research suggests that, in the Great Plains of the United States south of the Canadian Prairies, sand dunes and sand sheets are likely to become reactivated under predicted greenhouse climate effects of increased temperature and reduced precipitation (Muhs and Maat, 1993). In Canada, however, the sensitivity of eolian processes to climate change is largely unstudied.

The purpose of this report is to indicate the relationship between eolian processes and climate and how the extent and level of eolian activity in Canada may change in response to anticipated climate change. The factors controlling eolian processes are outlined, including the general mechanics and components of the eolian process system. The concept of climate change is discussed and potential scenarios based on a scenario of CO_2 doubling are reviewed. Areas of Canada that are currently affected by eolian activity are discussed together with the potential change in eolian activity which might result from climate change. A discussion of the relative sensitivity of sand dunes and agricultural lands to potential climate change in Canada is presented, based on a specific scenario, in conjunction with a summary map.

This report is a broad overview. It lays out the general principles underlying eolian processes, indicating how these impact on human activities and how eolian activity will probably be modified by global climate change. The report is not intended as an extensive study of the subject, nor is it intended to predict the exact changes which will occur. Instead, it is meant to illustrate that climate change could, and likely will, cause changes in the way geological processes affect the Earth's surface. These changes could initiate erosion or result in deposition of materials in areas that are currently stable and, in general, affect human activity. It is hoped that the alert raised by this report will encourage more specific studies of potential changes in eolian activity and into mitigating against the possible detrimental effects of global climate change.

CONTROLS ON EOLIAN PROCESSES

The following section discusses the general nature and results of wind erosion and deposition, and considers the environmental variables which control the distribution and level of eolian activity. Specifically, it looks at the entrainment and transport of sediment by wind and the components of the eolian process system. Two different sets of conditions, supply limited and transport limited, are defined followed by a discussion of the nature and distribution of winds in Canada. The majority of this section outlines the variables controlling erosion and transport of materials, including vegetation, soil moisture, and bonding agents. The final part outlines the approach used for mapping wind erosion risk of bare unprotected mineral soils and soils protected by a partial crop cover. A review of wind erosion mechanics and the principal factors controlling sediment transport by wind is given in the Appendix.

Components of the eolian process system

Sediment entrainment and transport

The entrainment and transport of sediment by wind results from a complex interaction of atmospheric, surficial, and textural variables (Table 1). In general, wind erosion can be classified as either transport limited or supply limited depending on the wind speed and availability of sediment at the surface. If the wind speed is sufficiently high and the eroding surface overlies an abundant supply of dry, loose sediment, wind erosion will be limited by the ability of the wind to transport the available sediment (transport limited). In contrast, if the surface is unable to supply sediment to the air stream in relation to the transport capacity of the wind, this can be viewed as being supply limited. Numerous factors can affect the availability of sediment, including sediment size,

Table 1. Factors influencing wind erosion (modified from Chepil, 1945).

Air	Ground	Sediment
Velocity profile	Roughness elements a) Height b) Spacing	Structure a) Texture b) Organic matter
Fetch length	Topography	Density
Turbulence	Obstructions	Moisture content
Density a) Temperature b) Pressure c) Humidity	Surface cover a) Vegetation b) Snow	Bonding agents a) Soluble salts b) Algae c) Silts and clays d) Ice
Viscosity		

surface soil moisture, vegetation cover, snow cover, crusting, intergranular ice, and the presence of precipitated salts. These factors determine the wind speed required to initiate transport and the supply of grains available to the air stream. Furthermore, these factors vary both spatially and temporally, complicating the pattern of wind erosion.

Nature and distribution of winds in Canada

Wind erosion in Canada most frequently occurs where moderate to high wind speeds are found in association with dry, loose sediment that is unprotected from the force of the wind. In such places the primary forcing variable for erosion is wind speed. Figure 2 illustrates the mean wind speeds for the period of 1967 to 1976, based on hourly data collected from 144 stations across Canada (Walmsley and Morris, 1992). The figure indicates that the highest wind regimes (>25 kilometres per hour) are found along the coastal regions of Canada. In addition, mean wind speeds of more than 20km/h occur within the southern portions of Alberta and Saskatchewan and in the Hudson Bay and central Arctic regions of Canada. Wind is often associated with specific synoptic conditions that are, in some instances, influenced or enhanced by topographic controls. These synoptic conditions include:

- frontal activity, particularly the passage of cold fronts,
- downdraughts associated with convective storm activity,
- steep pressure gradients between high and low pressure systems,
- katabatic drainage, and
- chinooks.

Frontal winds

In Canada, wind erosion events are often associated with the passage of warm and cold fronts that follow fairly well defined storm tracks. In Western Canada, fronts move in a dominant west to east pattern and are steered by the westerly jet stream. In Eastern Canada frontal activity is also often associated with storm systems that initially develop in the southeastern United States and over the Gulf of Mexico. These storm systems generally move up the Mississippi River valley into the Great Lakes region and then in an easterly direction along the St. Lawrence Lowlands to the Atlantic Ocean.

Most wind erosion events appear to be related to two distinct types of wind conditions that may be encountered as a front passes a given location. The first and most common situation occurs when wind erosion is initiated by strong winds associated with the leading edge of the front,

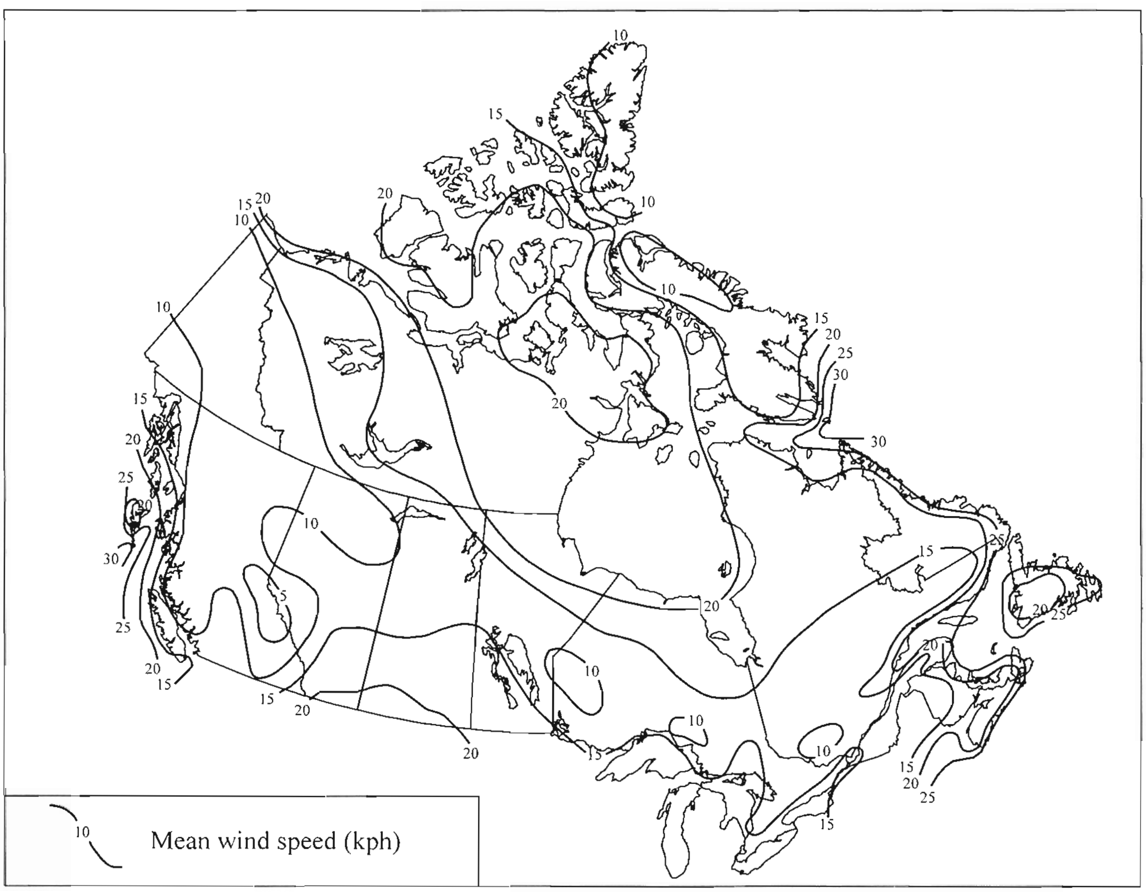


Figure 2. *Mean wind speed for the period 1967-1976 (after Walmsley and Morris, 1992).*

particularly cold fronts. Strong winds and wind erosion can also occur when a high pressure area builds in rapidly behind a front, sustaining high wind speeds for a considerable period of time (Brazel and Nickling, 1986). In both cases, wind erosion will occur as long as the surface is not fully wetted by precipitation. Throughout Canada, the highest wind speeds are usually associated with the passage of cold fronts in the presence of unstable air masses (Wheaton and Chakravarti, 1987).

Convective storms

Differential heating of the surface during the summer months may result in the development of localized thunderstorms, which can vary greatly in both size and frequency. Once developed, these cells can become organized into squall lines and move with the regional wind. In unstable air masses they can result in violent thunderstorms (with or without precipitation) that generate intense downdraughts and spread out laterally at the surface. If precipitation is limited, these high speed, surface winds may generate severe wind erosion events. Convectional storms of this nature have been associated with the development of major dust storms on the Canadian Prairies (Wheaton and Chakravarti, 1987) and localized, but intense wind erosion on agricultural fields in Ontario (Nickling, 1987).

Pressure gradient winds

Wind erosion, particularly in the prairies, can also be initiated by strong winds associated with steep pressure gradients between high and low pressure systems. A strong outpouring of air in the transition zone between the pressure systems can occur at any time during the day or night and last for extended periods. Wheaton and Chakravarti (1987) found that atmospheric conditions of this type are often responsible for the erosion of agricultural soils and generation of major dust storms in southern Saskatchewan. Pressure gradient winds can also result in soil losses on sandy agricultural soils in southwestern Ontario in the spring when fields are bare and dry following cultivation (Nickling and FitzSimons, 1985).

Katabatic winds

In mountainous regions, relatively high wind velocities are frequently associated with the down slope and/or down valley drainage of cool air (Fleagle, 1950; Tyson, 1968; Nickling and Brazel, 1985). During the late afternoon and evening, air in contact with the valley side slopes begins to cool and move down slope, collecting in the valley basins. As the relatively cool, dense air accumulates it begins to flow down valley and merges with air draining from tributary valleys. As a result of the down slope accumulation and the constriction of the valley walls, the air flow may accelerate and, under some conditions, reach very high speeds in the lower parts of the valleys.

Katabatic drainage is best developed under clear sky conditions at night, promoting radiative cooling of the valley side slopes and where large temperature gradients exist along the length and breadth of the valleys. The most notable situation is where glaciers head the valleys, providing a source and reservoir of cold dense air that readily drains down the valleys, particularly at night. Katabatic drainage is also enhanced when regional pressure gradients and wind directions are in alignment with the valleys (Manins and Sawford, 1979; Nickling and Brazel, 1985).

Katabatic winds have been cited as a principal mechanism for wind erosion, dust storm generation, and the development and maintenance of dunes in the interior valleys of southwestern British Columbia (Coote et al., 1982), in the Yukon Territory (Nickling, 1978), and on Baffin Island (McKenna Neuman, 1990a).

Chinook winds

In southwestern Alberta, wind erosion is periodically associated with strong westerly winds that flow down the eastern flank of the Rocky Mountains. These winds, locally termed chinooks, result from the eastward flow of relatively warm, moist, unstable air along steep pressure gradients over the Rockies from the Pacific Ocean. As the air encounters the mountain barrier it converges and is forced to ascend and cool. If the dew point of the air is reached, condensation occurs resulting in precipitation primarily on the western flank. After crossing the mountains, the dry air diverges and flows down the eastern slopes, warming adiabatically and drying as it descends. These dry, warm winds blow out across the prairies and obtain very high speeds when the regional pressure gradient is large. The high wind speeds, in association with the desiccating effect of the dry air, can result in deflation (erosion by wind) even during winter months, particularly on bare agricultural fields (Wheaton and Chakravarti, 1987).

Variables controlling entrainment

In many situations, even though the wind speed is relatively high, entrainment and transport of sediment will not occur because surface soil conditions, vegetation cover, or some other factor limits the availability of materials resulting in a supply limited condition. At present, our ability to predict threshold and sediment transport rates for complex systems (for example: agricultural soils and, semi-arid and coastal environments) is much more limited than for a relatively simple system involving dry, loose sediments. During the past decade considerable attention has been given to the more complex systems and has provided important basic relationships that aid in predicting erosion thresholds and sediment transport rates.

For example, the presence of large roughness elements on the surface, such as clods formed by tillage operations or gravel lag deposits resulting from the selective removal of fines by both wind and water, inhibit deflation. Lyles et al. (1974) and Lyles (1977) showed that as surface roughness increases, a greater proportion of the wind shear stress is taken up by the larger nonerodible roughness elements, leaving less shear stress to entrain the finer, more erodible particles resting below the clods or gravel lag. Wind tunnel experiments by Logie (1981) also indicated the importance of roughness element spacing on threshold velocity and the nature of particle entrainment. High densities of roughness elements increase velocity of wind that must be reached before particles will be moved and thus reduce erosion. In contrast, however, low densities of roughness elements tend to reduce threshold velocity and cause increased erosion around the roughness elements because of the development of turbulent eddies.

In addition, natural sediments are not usually found in a dry, loose state but are more frequently bound together by agents such as moisture, clay, algae, or precipitated salts. Surface crusts, formed by various bonding agents, inhibit wind erosion by increasing the surface threshold velocity required to begin moving grains. Clay- and silt-rich crusts can be formed by raindrop impact and by the sedimentation of fines transported by sheet and rill wash during intense rainfall events (Chen et al., 1980). The presence of algae and fungi have also been shown to contribute to crust formation on coastal dunes (Foster and Nicolson, 1980; Van den Ancker et al., 1985) as have the precipitation of soluble salts on agricultural soils and in arid regions (Lyles and Schrandt, 1972; Nickling, 1978; Pye, 1980; Gillette et al., 1982).

Vegetation

Perhaps the single most important variable in the control of wind erosion is vegetation. As shown in Figure 3, vegetation suppresses deflation in three principal ways:

- reducing the availability of sediment by covering the soil
- absorbing wind momentum and thereby reducing the velocity at the surface, and
- trapping moving sediment.

Numerous authors, working in many parts of the world and different environments, have demonstrated that vegetation plays a critical role in suppressing deflation. The lack of or removal of natural vegetation cover has been linked to increased wind erosion in Canada on natural surfaces (Nickling, 1978; McKenna Neuman, 1990a), on coastal sand dunes (McCann, 1975; Saunders and Davidson-Arnott, 1990), and agricultural fields (Coote et al., 1982; Nickling and FitzSimons, 1985; Wheaton and Chakravarti, 1987, 1990).

Surface soil moisture

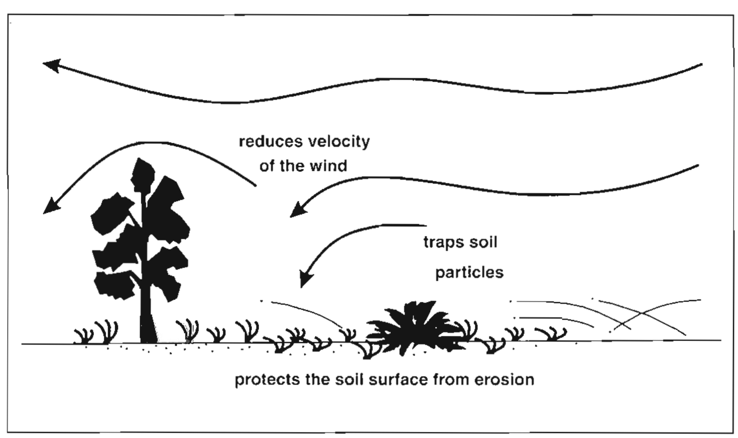
Field observations and wind tunnel studies have shown that surface soil moisture content is one of the more important variables controlling both the entrainment and transport of sediment by wind (Bisal and Hsieh, 1966; Azizov, 1977; McKenna Neuman and Nickling, 1989). Belly (1964) showed that (gravimetric) surface soil moisture contents of 0.6% and less can more than double the threshold velocity of medium-sized sands. Above 5% moisture content, sand-sized material is inherently resistant to entrainment by most natural winds. Consequently, wind erosion on agricultural fields and sand dunes may be suppressed by even small amounts of surface soil moisture. The cohesion of sand grains due to moisture content may be overcome by increases in the surface wind speed due to topographic effects and reduced sand transport, thereby initiating erosion. In particular, David (1978) suggests that the characteristic parabolic form of many sand dunes in Canada is the result of the continuous presence of soil moisture in dunes.

Other bonding agents

Work by Chepil (1951) on agricultural soils has shown that the presence of organic matter increases the ability of particles to form aggregates that are less susceptible to entrainment by wind than the individual grains. Chepil and Woodruff (1963) observed that the effectiveness of silt and clay as bonding agents depends on their relative proportion in relation to the quantity of sand-sized material. They suggested that soils having 20 to 30% clay, 40 to 50% silt, and 20 to 40% sand produce the greatest number of nonerodible clods with the highest degree of mechanical stability and are least affected by abrasion. In contrast, light textured, sandy soils, particularly if organic matter contents are low and

Figure 3.

The protective role of vegetation (adapted from Wolfe and Nickling, 1993).



natural soil structure is broken down by tillage, will be highly susceptible to deflation. This is evident by the relatively high degree of wind erosion observed on the sandy soils of southwestern Ontario where continuous corn cultivation dominates (Nickling and FitzSimons, 1985).

The presence of ice in soil has been shown to reduce the rate of erosion on bare surfaces. Nevertheless, several mechanisms increase the erodibility of bare, frozen soil including loss of moisture through sublimation of the pore ice, and abrasion of the frozen surface by saltating sand (McKenna Neuman, 1989, 1990b). Erosion of clay soils observed in winter months on fallow farm fields in southern Manitoba has been attributed to a process of freezing followed by sublimation of intergranular ice, which produces soil pellets suitable for erosion by the wind (Teller, 1972). Anderson and Bisal (1969) have shown that the removal of pore ice through sublimation enhances the subsequent breakdown of soil aggregates on agricultural soils, so that exposed surfaces may be highly susceptible to wind erosion in late winter.

Finally, Nickling (1978, 1984) and Nickling and Ecclestone (1981) have shown that even low concentrations of soluble salts can significantly increase threshold velocity by the formation of bonds between individual particles. Lyles and Schrandt (1972) noted that sodium chloride was more effective than magnesium chloride and calcium chloride in reducing soil movement because sodium chloride tends to produce a surface crust which protects the underlying soils. Consequently, increased soil salinity due to irrigation and surface evaporation, although detrimental to agricultural production, does inhibit wind erosion.

Wind erosion risk

The previous sections reviewed several of the components involved in the eolian process system. Additional background into the mechanics involved in wind erosion are reviewed in the Appendix. However, due to the large number of factors influencing eolian processes, it is difficult to predict thresholds and transport rates for erosion of soil material by wind on a theoretical basis alone. For most practical purposes an empirical approach is taken in which wind erosion or the risk of wind erosion (being the potential for wind erosion under given circumstances) is estimated primarily on the basis of controlled experimental observations.

The present classification of the risk of wind erosion of bare, unprotected mineral soils in Canada is based largely on the experimental work of Chepil (1945, 1956) and Chepil and Woodruff (1963) in developing a wind erosion equation for agricultural soils (Coote et al., 1987a, b; Coote and Padbury, 1987).

The model presently used by Agriculture Canada in the preparation of maps on wind erosion risk of bare, unprotected mineral soils is:

$$E = KC(u_*^2 - \gamma W^2)^{1.5}$$

where:

E is the maximum instantaneous soil movement,

K is the surface roughness and aggregation factor,

C is a factor representing soil resistance to movement by wind,

u_* is the shear (drag) velocity of wind at the soil surface,

γ is the soil moisture shear resistance, and

W is the surface soil available moisture content (volumetric).

The model primarily reflects the components of soil availability, wind, and resistance to erosion due to moisture, surface roughness, and aggregation. Estimates of E, K, and γ are made from the texture of the soil surface and adjusted to reflect soil behaviour during April and May, reflecting the most erosion-prone period of the year. Shear velocities (u_*) are derived from mean maximum one-hour wind speeds for April and May (see Appendix for discussion of u_*). The remaining variable (W) is a function of the available soil moisture and is estimated using long-term climatic data. In this equation, soil moisture plays a primary role in reducing the wind erosion risk of the bare unprotected soil.

Estimates have also been made of the percentage reduction of wind erosion risk due to crop cover and crop residue on prairie farmland. These estimates take into account the protection provided by crop cover in reducing wind erosion on agricultural soils and account for probable yields and likely tillage practices (Coote et al., 1987a, b; Coote and Padbury, 1987). For the purposes of assessing climatic sensitivity, however, this report will focus on the wind erosion risk of the bare, unprotected soil. Although cropping practices will almost certainly change in the future, it would be extremely speculative to assess how these changes will affect wind erosion.

CLIMATE CHANGE IN CANADA

Climate change

Documentation of climate, including temperature, precipitation, and wind speed are generally limited in North America to the past one hundred years or less. Consequently, our knowledge of the norms, extremes, and variability associated with the climate is based on a relatively short period of measurement. To determine the climate over longer periods, proxy sources including tree rings, ice cores, lake sediments, and pollen are used. In general, this information indicates that the global climate has always been in a state of change, both in the short-term scale of a few seasons or decades and in the long-term historical and geological scale.

While scientists argue about the exact causes of past climate change, they agree that these changes have greatly affected ecosystems and landscape-forming processes of North America. During the height of the most recent glacial period, about 18 000 years ago, thick ice sheets covered most of Canada and extended into the United States. As warmer climatic conditions prevailed, the glaciers melted and vegetation recolonized much of the landscape. Since that time, there have been several periods in which the climate of North America has been warmer and drier, as well as colder and wetter, than it is today. For example, the Climatic Optimum (or Hypsithermal period) ranging from 9000 to 4000 years ago and the Medieval Warm Period of 1000 to 600 years ago were two periods that were warmer than at present. Although the Canadian landscape is largely dominated by features of the last glaciation, much of the landscape has been modified by subsequent geomorphic processes including coastal, biotic, slope, fluvial, permafrost, and eolian activity. The intensity and spatial extent of these processes depends, to a large extent, on the past and present prevailing climate. Consequently, the nature and intensities of geomorphic processes in Canada differ from one geographic and climatic region to the next and also have varied through time as the climate has changed.

Recently, attention has focused on a new cause of potential climate change, derived primarily from human sources. High concentrations of CO_2 and other gases in the atmosphere have resulted from the burning of fossil fuels and a variety of other activities since the start of the Industrial Revolution. These gases are anticipated to induce environmental changes leading to climatic warming in a manner analogous to how a greenhouse becomes warmer than its surroundings (MacCracken, 1988). The premise is that, while essentially transparent to incoming solar radiation, CO_2 and other greenhouse gases trap and reradiate surface infrared radiation back towards the Earth where it is absorbed and turned into heat. It has been estimated that CO_2 is being added to the atmosphere at a rate which will result in a concentration equal to twice that of the pre-Industrial Revolution by the year 2100 (Nordhaus and Yohe, 1983).

During the 1980s, several scientific institutions produced general circulation models (GCMs) to simulate the effects of doubling atmospheric CO_2 concentrations on the global climate. While the results vary quantitatively, the general consensus is that global warming will occur. Simulated increases in the annual, global-mean surface temperature range between 2.8°C and 5.8°C and corresponding increases in precipitation range from 7.1% to 15.0% (Schlesinger, 1987) over the next century. The models predict that change will not be uniform across the globe. The greatest warming is predicted in the polar regions with summertime warming increasing by approximately 2°C while fall temperatures increase by 8°C to 16°C (Schlesinger, 1987). In North America most models predict warming to increase with latitude with increases of 4°C in the south and 10°C in the north. In addition, summertime warming is generally predicted to be less than winter warming. Furthermore, the models suggest increased soil water during winter while most indicate lower summer soil surface water across North America due to increased evapotranspiration.

More recently, a second-generation general circulation model was released by the Canadian Climate Centre (Boer et al., 1992; McFarlane et al., 1992), which parallelled the results of the earlier models. The Canadian Climate Centre second-generation model predicts a global warming of 3.5°C, with enhanced warming found over land and at high latitudes, and with precipitation and evaporation rates increased by 4% (Boer et al., 1992). With respect to Canada, mean annual surface air temperatures are predicted to increase by approximately 4°C in central Canada in summer and winter. In general, the proportion of winter precipitation falling as snow, and the total soil moisture availability in summer, is predicted to decrease.

The simulated climatic scenarios of the general circulation models have raised numerous concerns regarding the predicted shifts towards climatic warming in Canada. These include: 1) the potential for larger percentage of winter precipitation to fall as rain, thereby reducing spring snow-melt; 2) that summer precipitation may be insufficient to offset increased evapotranspiration rates caused by warmer temperatures; and 3) that extreme conditions such as drought will occur with greater frequency than at present. Of additional concerns that have also been raised, perhaps foremost is the rate at which climatic warming could occur. Although our climate has varied considerably in the last 10 000 years, the rate of change brought about by an increase in greenhouse gases could be 10 to 40 times faster than the average warming following deglaciation (Rizzo and Wiken, 1992). This rate of climatic warming could lead to shifts in the range and abundance of plant species much more rapidly than in the past. The ability of natural systems to adapt to the rapid imposition of new climatic conditions is poorly understood (MacCracken, 1988).

Within each region of Canada the natural environment has adapted to the past and present climate and geomorphic processes of that region. Because geomorphic processes are firmly linked to climate, climate change may have significant consequences on the nature and levels of process activity and hence on rates of erosion, deposition, and landscape evolution. Thus, the potential response of geomorphic processes to climate change is of concern. Climate warming over the next 50 to 100 years could cause significantly different landscape developments than at present by accelerating change in geomorphic processes. In addition, the rate and level of change will vary spatially and through time, depending on the geographical setting and particular geomorphic processes.

Potential effects of climate change

Results of general circulation model simulations have been used by a number of researchers to determine the potential effects of climate change in Canada. Eolian processes are sensitive to various aspects of the prevailing climate. In the short term, climate-induced changes in temperature and precipitation may affect eolian processes by affecting the threshold velocity required to initiate transport of sediment. More importantly, however, are the longer term changes that might occur as a result of regional climatic shifts. These could alter the availability of sediment for transport by affecting the amount and type of natural vegetation cover or the extent of cultivation of agricultural land. Such changes could have a significant effect on eolian processes by altering the protection provided by vegetation cover. In the long term, natural systems will adjust to the effect of climate change, although the level of eolian activity may change. Similarly, people may be forced to adjust agricultural cropping practices and introduce mitigating measures against the effect of climate change on agricultural land.

Regional associations of climate and vegetation can be classified and mapped as life-zones or ecoclimatic regions (Holdridge, 1947; Rizzo and Wiken, 1992). Temperature and precipitation are principal controls for ecosystems existing within these regions, as they significantly influence such factors as energy and moisture balances and productivity rates (Rizzo and Wiken, 1992). With the recognition that such climatic indices are principal controlling factors for ecosystems, climate change has the potential of shifting and altering ecoclimatic regions, which in turn can affect geomorphic processes within these systems. Figure 1, inset A, based on work by the Ecoregions Working Group (1989), shows the present-day delineation of ecoclimatic regions based on precipitation and temperature regimes within Canada. At present, the boreal zone is the most extensive Canadian ecoregion, extending as a broad band from the western Cordillera to the Maritimes. The subarctic and arctic zones are similarly large, extending across the continent in latitudinal bands. The milder ecoclimatic regions occupy smaller proportions of land, including the grassland region in the mid-west and the cool and moderate temperate zones in the east. While the extent and level of eolian activity varies across Canada, as well as within specific regions, the climatic factors responsible for regional aspects of eolian activity are generally roughly similar throughout any given ecoclimatic region.

Rizzo and Wiken (1989, 1992) have examined the sensitivity of Canada's ecoclimatic regions to climate change based on a CO_2 doubling scenario from the Goddard Institute for Space Studies general circulation model (Hansen et al., 1983). Climate change associated with increased CO_2 concentrations will alter the distribution and the relative proportion of all the ecoclimatic regions in Canada. Figure 1, inset B depicts the scenario from Rizzo and Wiken (1989, 1992) of the potential changes to these regions based on a doubling of atmospheric CO_2 concentrations. The cool temperate regions show the greatest predicted increase in land area while the boreal and subarctic regions show the greatest decline. The grasslands and cool temperate regions increase largely at the expense of the boreal regions. In addition, under the predicted scenario, the grasslands regions of southern Alberta and Saskatchewan may change to semidesert, an ecoclimatic region not presently found in Canada. A change from grassland to semidesert would alter the type and abundance of vegetation covering the ground surface. Alterations in the amount of vegetation cover associated with changes in ecoclimatic regions may result in changes in eolian activity within these regions. Similarly, changes in precipitation and temperature regimes accompanying shifts in ecoclimatic regions will bring about changes, not only in the susceptibility of agricultural land to wind erosion, but also to the viability of the land for cultivation.

One point which must be kept in mind, is that climate change is unlikely to result in unrestricted shifts of ecoclimatic regions to areas that are climatically most suitable since ecoclimate regions are also a function of existing soils and physiography (Rizzo and Wiken, 1992). For example, it is unlikely that prairie grasses and associated environment will extend into the Canadian Shield due to the differences in existing soils. Nevertheless, changes in temperature and soil moisture will likely affect the amount and type of vegetation cover to some extent, potentially altering present eolian activity.

Climatic conditions coupled with agricultural practices, also affect the sensitivity of agricultural soil to wind erosion. Some agricultural practices reduce the surface cover for part of the year, typically from fall through spring, thereby exposing the soil to potential wind erosion. In addition, during drought periods the protective cover of crops during the growing season may be decreased because of lower biological productivity. Smit (1987) has suggested that large increases in potential evapotranspiration brought about by climate change would negate the agricultural benefits of increased precipitation in southern Ontario. Consequently, crop failures may be more common in the agricultural heartland of Ontario. In the Prairie Provinces, it is believed that droughts could become more frequent and severe, with a potential return period of "severe drought" of only about half as long as at present (Stewart et al., 1987). Increased drought frequency may, in turn, increase the frequency and magnitude of wind erosion on agricultural lands by increasing the proportion of soil exposed. While it is possible that climate change may affect the extent and level of wind erosion on agricultural soil, agricultural practices could be changed to mitigate against an increased potential of wind erosion although there are practical limits to the extent to which this could be done.

Climate change is also likely to bring about changes in river discharges, lake levels, and sea levels. Rivers carry large amounts of sediment that may be deposited as deltas or transported from the river mouth to form beaches and coastal sand dunes. Changes in water levels and river discharges will change the amount of sediment exposed in floodplains, delivered to deltas, and in other ways made available for eolian transport.

Human impact on the environment will also change, including urbanization, agriculture, and recreational land use, and could significantly affect the response of natural systems to climate change. For example, the opening up of new agricultural land may accompany climate warming in some regions. This would mean clearing natural vegetation and exposing new areas to wind erosion. On the other hand, some of the more arid regions could be taken out of crop production. It is even possible that increasing aridity might result in a decrease of pasture land use in some portions of the southern Prairie Provinces. The extent to which eolian and other geomorphic processes are affected by climate change will be profoundly influenced by human impact on the environment.

The concern over climate change in Canada poses numerous questions with respect to the potential effects on eolian processes. For example, will stabilized dunes be reactivated? Will wind erosion on farmlands increase and will dust storms be more frequent and severe? Could persistent drought result in a return to the "Dust Bowl" conditions of the 1930s? The following section outlines the present state of eolian activity in Canada and discusses the effects that climate change may have on eolian activity.

IMPACT ON EOLIAN PROCESSES

The impact of climate change on eolian processes in Canada may be deduced, in part, from the past and present extent of eolian activity. As discussed earlier, eolian activity in Canada is a product of sediment supply, wind regime, vegetation cover, soil moisture, and other factors. Present eolian deposits and features indicate areas that may be most susceptible to eolian activity as they may be the first affected in periods of enhanced activity. This section reviews eolian processes as they presently affect the landmass of Canada. In addition, it discusses the origins of eolian deposits and the sensitivity of eolian activity to climate change. The review primarily covers sand dunes and wind erosion of agricultural soils.

Sand dunes

Evidence of past eolian activity in Canada is found in the form of loess deposits, wind-drifted soil, sand dunes, and wind-eroded soil and bedrock. Sand dunes are not only one of the most prominent features of eolian activity in Canada, being visually impressive (Fig. 4), but are excellent indicators of past eolian activity, recording evidence of past wind directions and periods of dune stabilization and reactivation.

Eolian sand dunes are typically mounds, hills, or ridges of sand that are capable of migrating under the transporting power of wind. Sand dunes are present in all provinces and territories of Canada. They occur inland and along lakes, rivers, and ocean shorelines. Eolian features and associated forms in Canada include parabolic dune assemblages, transverse dunes, coastal foredunes (dunes developed on the shoreward side of beach ridges), and cliff-top dunes.

The most common dune form in Canada is the parabolic dune (David, 1977). Parabolic dunes are typically arcuate and parabolic in form. Although many other associated forms are possible, depending upon sediment supply and wind conditions (David, 1977; Halsey et al., 1990), in all cases the arms of the dunes point upwind (Fig. 5). According to David (1978), the presence of moist sand is integral to the development of parabolic dunes. Parabolic dunes may develop through the mobilization of an original unvegetated sandy deposit or from the deflation of another dune form or stabilized surface. Parabolic dunes also occur as secondary features on coastal foredunes. Coastal foredunes form adjacent to the landward edge of a beach and are supplied by sand blown from the beach. In Canada, these dunes are typically fixed by vegetation such as marram grass. The vegetation cover on foredunes is commonly broken, permitting deflation hollows or blowouts to form (Fig. 6). In some instances, as

Figure 4.

Transverse dunes in the east central part of the east dune field of the Athabasca Sand Dunes (photo courtesy of D. Smith). ISPG 4236-5

Figure 5.

A parabolic dune depicting deflation hollow and arms pointing in upwind direction.

shown in Figure 7, extension of the blowouts produce parabolic dune forms or coastal blowout dunes that migrate inland from the foredune area. Other eolian sand features in Canada include sand sheets, which are accumulations of windblown sand of varying thickness without pronounced eolian relief (David, 1977) and dome dunes which are rounded, circular to elliptical dunes without slip faces or deflation hollows (Halsey and Catto, 1994).

Blowouts and deflation surfaces are often associated with most of the eolian landforms mentioned above (Fig. 7). Blowouts form by deflation of sand through a breach in the vegetation cover or some other form of surface protection (David, 1977). Blowouts typically form smooth or irregular bowl-shaped depressions as the sand is deflated from the area. A deflation surface is the area from which sand is, or has been, removed. Typically a lag of pebbles or moist sand and soil develops on deflation surfaces as the mobile sediment is blown away. Blowouts and deflation surfaces are common on many of the partially stabilized eolian deposits in Canada.

Figure 8 depicts the distribution of eolian sand dunes in Canada based on the reports of David (1977, 1989) and supplemented by additional sources (McCann, 1975, 1990; McKenna Neuman, 1990a; Hales, 1993). The map depicts known sand dune regions, highlighting those greater than 26 km^2 in area. In many regions, the dunes are partially or completely stabilized by vegetation. Eolian processes are active, however, wherever wind action mobilizes sand or fine grained soil. The impact of climate change on sand dunes in Canada depends upon the present state of eolian activity and on the relative changes in the various aspects of the eolian process system induced by climate change

Inland regions

Many of the inland sand dune deposits in Canada developed soon after deglaciation. At this time, dry winds along the continental glacial margin mobilized sandy sediments into dunes (David, 1981). The source material for these dunes was primarily the abundant deltas, outwash, or other glaciolacustrine or glaciofluvial deposits (Trenhaile, 1990). Eolian activity was intensified at this time by the lack of vegetation covering the landscape. Climatic conditions of this period were cool and dry (David, 1981) and were not the hot desert conditions that are associated with many active sand dunes in other parts of the world today. To date, the most complete study detailing the location and morphology of sand dunes in Canada is that of David (1977). The description of the following sand dune occurrences in Canada is derived primarily from this work.

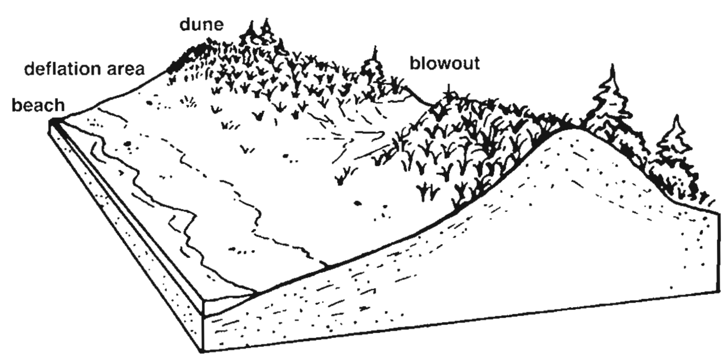


Figure 6.

A coastal foredune with blowout, beach, and deflation area.

Figure 7.

Blowouts in older dune ridges, Dune du Sud, coast of îles de la Madeleine, Quebec (photo courtesy of S.B. McCann). GSC 1995-065

The largest number of dune occurrences are in Alberta, with over 30 reaching in excess of 26 km^2 [1]. The largest of these, spanning the borders of northern Alberta and Saskatchewan, are the dunes of the Lake Athabasca region, which exceed a total area of 4781 km^2 (Smith, 1978). The dunes are derived from local deltaic deposits, outwash, and glaciolacustrine sediments. The dunes represent the largest contiguous active sand dune occurrence in the glaciated regions of North America (David, 1980) and reside within the boreal ecoclimatic region of Canada. Other sand dune occurrences in Alberta residing in the boreal region include dunes of Wood Buffalo National Park and the sandhills in the Fort McMurray area. Other dune areas, including The Middle Sand Hills near Medicine Hat, reside within the grassland ecoclimatic region. With the exception of the Athabasca sand dunes, most of the sand dunes are stabilized, with a few scattered blowouts.

Saskatchewan has been climatically suitable for the development of sand dunes and yet it has fewer dune area occurrences than Alberta. David (1977), ascribes this to the fact that large parts of southern Saskatchewan are covered by fine grained glaciolacustrine deposits unsuitable for dune development. Nevertheless, because of the arid climate, the greatest variety of dune forms and associations are found in Saskatchewan with a total of 23 occurrences exceeding 26 km^2 in area. The largest contiguous sand dunes in the Canadian Prairies are the Great Sand Hills in southwestern Saskatchewan. These dunes cover 1070 km^2 and are derived from glaciolacustrine and glaciofluvial deposits. Blowouts and stabilized parabolic dunes are common while present-day activity is sporadic (Fig. 9).

There are numerous small dune fields in Manitoba including those in the vicinity of Portage la Prairie. The largest dune occurrence in Manitoba is the Brandon Hills, with a central area covering approximately 965 km^2 and comprising a number of separate or loosely connected sectors (David,

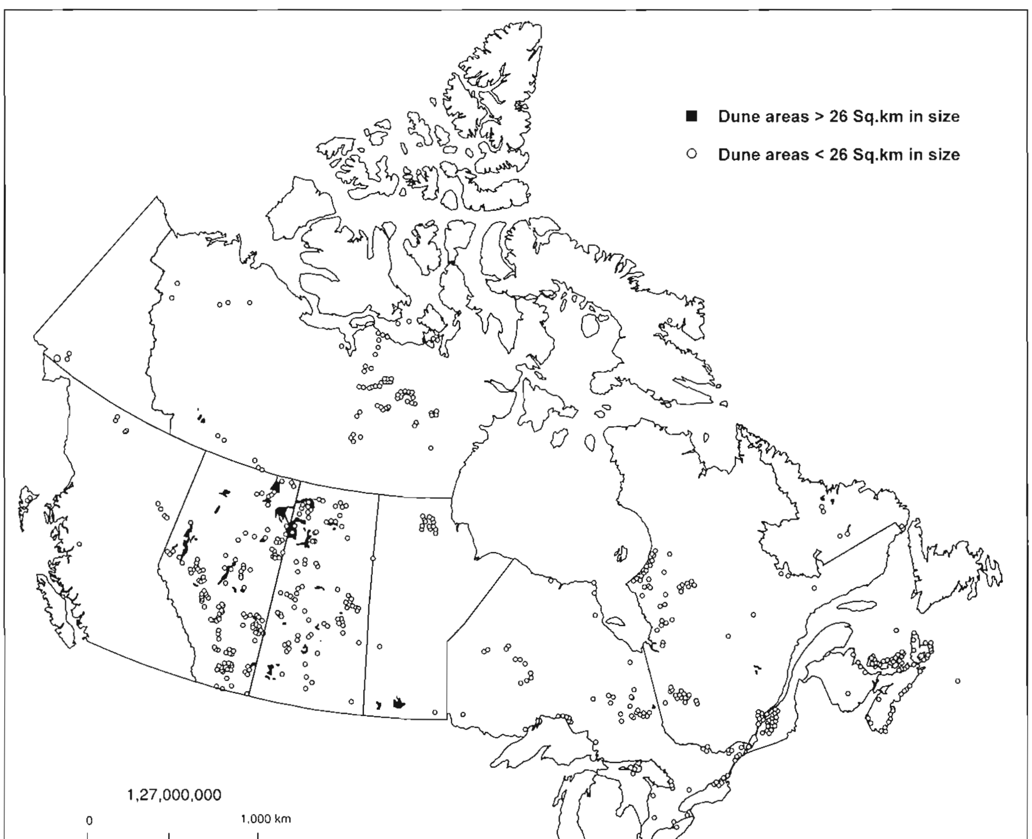


Figure 8. *Dune areas in Canada (after David, 1977, 1989), with additional sources from McCann (1975, 1990), Hales (1993), and McKenna Neuman (1990a).*

[1] 26 km^2 is the minimum size of dune included in the inventory of David (1977).

1977). It is the second largest on the Canadian Prairies and resides within the present grassland ecoclimatic region. The sand hills are derived from the Assiniboine delta of glacial Lake Agassiz and contain numerous blowouts, hills, and elongated parabolic dunes. According to David (1971), the Brandon Hills have undergone several periods of reactivation in the last 4000 years with some forms still active today.

There are numerous sand dune occurrences in Ontario, three of which exceed an area of 26 km^2. The lack of larger dunes in Ontario is due, primarily, to small and sporadic source deposits, local topography preventing sufficiently strong surface winds, the rapid invasion of vegetation, and changes in drainage patterns following deglaciation (David, 1977). The three largest inland sand dune occurrences in Ontario occur in the vicinity of Kirkland Lake. They are principally parabolic dunes derived from glaciolacustrine and glaciofluvial and outwash deposits and together exceed 259 km^2 in area. The inland dunes of Ontario are largely inactive, due primarily to the dense vegetation cover within the boreal and cool temperate ecoclimatic regions. In the past, however, logging and farming has partially reactivated dunes and eolian processes in some areas.

Many parts of Quebec contain sporadic occurrences of sand dunes, with only a few reaching a significant size. The greatest concentration of dunes occur in the arctic and subarctic regions east of James Bay and Hudson Bay with source material derived from marine, deltaic, and fluvial sands (Filion and Morriset, 1983) and are primarily stabilized parabolic dunes. There are also extensive stabilized sand dunes in the boreal zone of the Lac Saint-Jean region and St. Lawrence Lowlands of Quebec. The Lac Saint-Jean dunes are derived from deltaic deposits and cover an area greater than 259 km^2. The present-day activity of these dunes is restricted to small patches at the top of individual dunes, except in some areas where a relatively large number of dunes show activity at the top (David, 1977).

Sand dunes are rare in Newfoundland, while three dune fields occur in low-lying areas of Labrador and are derived from fluvial or glaciofluvial deposits. There are no known

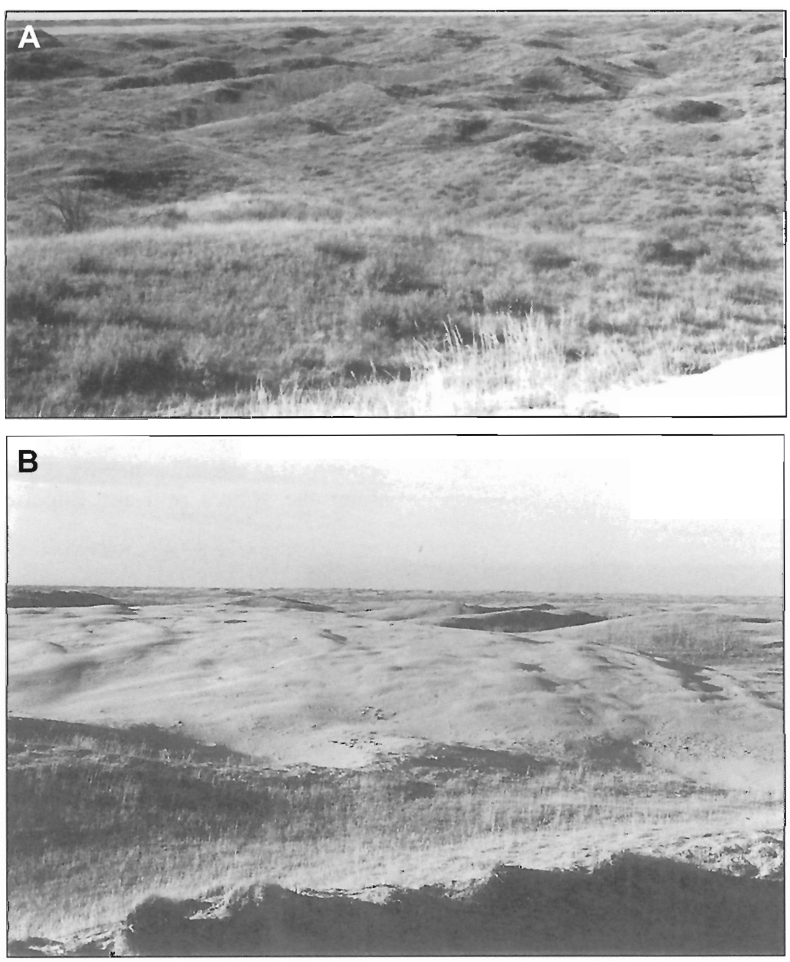


Figure 9. *Great Sand Hills of Saskatchewan (photos by S. Wolfe):* ***A)*** *Vegetated, stabilized dune area, south-central part of region; ISPG 4236-7;* ***B)*** *Active dune area, northwest part of region; ISPG 4236-8*

inland dune occurrences of significant size in any of the Maritime Provinces. Although there is an abundance of sandy deposits in all of these provinces, the lack of dunes is largely attributable to physiographic, climatic, and vegetation factors (David, 1977). Finally, there are only a few rather small occurrences of sand dunes in British Columbia, most of which are located along river valleys or present-day alluvial plains.

Sand dunes, particularly in Saskatchewan and Alberta, are locally associated with loess. Loess is an eolian deposit consisting primarily of silt. It is derived through deflation of till and other glacially-derived sediments, in addition to the occurrences on the lee side of dune areas, it is common downwind from glaciofluvial deposits in the Cordillera (Trenhaile, 1990). With the exception of those in Yukon Territory and some other arid arctic regions in Canada, most loess deposits in Canada are inactive. The surface loess deposits of the prairies were deposited in the late Wisconsinan and early Holocene periods between 6000 and 13 000 BP (Vreeken, 1986, 1988). Once deposited, loess is typically stable and not prone to further deflation by wind.

With respect to climate change, the greatest eolian sensitivity is likely to be in southern Alberta and Saskatchewan. According the Rizzo and Wiken (1992) this region of grassland may change to semidesert as a consequence of warming (Inset B). Sand dunes in this region including Great Sand Hills of Saskatchewan and The Middle Sand Hills of Alberta could be partially reactivated if the vegetation cover is sufficiently reduced. However, a change in vegetation type and cover alone would not necessarily destabilize the bulk of the sand dunes of this region. For example, the sand hills of Nebraska, Texas, and New Mexico in the United States which are at present in a semidesert ecoclimatic region are largely stabilized by vegetation, despite the semi-arid climate and often sparse vegetation cover (Muhs and Maat, 1993). In most cases, recent remobilization of these sand hills has been accompanied by farming and overgrazing, although there is evidence for regional sand dune activity on the Great Plains related to a more arid climate in the period from about 3500 to 1500 years ago (Holliday, 1989; Gaylord, 1990). In some areas of southwestern Alberta, particularly around Lethbridge, winds associated with chinooks make that region vulnerable to eolian processes although, due to the lack of source sediment, there are fewer sand dunes occurrences in this region than to east. Nevertheless, a reduction in vegetation associated with a more arid environment could increase the risk of dune reactivation if land use activities are not adjusted to protect the dunes from disturbance.

Active dunes of the boreal and subarctic region, including the Athabasca sand dunes may also be affected by climate change. In this case, warming associated with climate change may bring about a milder climate and longer growing season, encouraging vegetation growth in the region. Consequently, much of the active areas of dunes may be stabilized by vegetation thereby reducing eolian activity. In other areas, such as near the eastern coast of Hudson Bay, sand dunes show a distinct change in pattern from forest-type systems that are sporadically active, to tundra-type systems that develop slowly over long periods of time. The limit between these eolian systems shows a zonation, marked by the treeline, which is climatically controlled (Filion and Morisset, 1983). Under the scenario proposed by Rizzo and Wiken (1992) the boreal forest will extend northward, across most of the eastern coast of Hudson Bay. Consequently, a change in eolian systems from tundra-type to forest-type may accompany the northward advance of the treeline in this region.

Dunes associated with modern alluvial terraces, deltas, and other fluvial deposits may be affected by changes in river discharges induced by climate change. Decreases in river discharge could expose more river bed deposits to eolian activity. Alternatively, increases in river discharge may increase the volume of sediment carried in rivers and left exposed on floodplains, subsequently increasing the amount of deltaic or channel deposits in some areas. In Pukaskwa Park and on the Pic River in Ontario, rivers erode sandy deposits that are subsequently deposited at the river mouths along the shores of Lake Superior. In many places this

Figure 10.

Transverse dune ridge migrating over a coniferous forest northwest of the Slims River delta, Yukon Territory (photo W.G. Nickling). GSC 1995-066 material is reworked by the wind to form dunes. In the Cordilleran region of Canada, including the Slims River delta in Yukon Territory, source material for eolian transport is derived from active deltas in times of low water (Fig. 10). Changes in river discharges affects eolian activity by regulating source material for subsequent transport by wind.

In most regions of Ontario, Quebec, and the Maritimes, a change to a more moderate climate is unlikely to bring about an increase in eolian activity on inland sand dunes. In these areas vegetation cover is likely to be sufficient in the cool temperate to moderate temperate ecoclimatic regions to maintain the stability of the dunes. In Newfoundland and Nova Scotia, the lack of dune building sediments restricts further sand dune development.

In addition to being sensitive to climate change, many sand dune areas have been greatly affected by human activity in the last two centuries. Logging, agriculture, and recreational activity has flattened or caused a reactivation of dunes in several parts of Canada. In a few cases disturbance has resulted in new dunes forming and migrating into forested areas or onto cultivated fields (Martini, 1981). In Western Canada, early settlement disturbance and Indian hunting activity may have been responsible for local reactivation of dunes (David, 1993).

Coastal regions

Atlantic coastal dunes

Coastal dunes are common along the shores of the Atlantic coast and the Great Lakes (Fig. 8). In coastal areas, sand transported landward from the beach and backshore by eolian processes is the principal sediment input to coastal sand dunes. In general, the sediment supplied to coastal dunes is derived from a narrow strip of beach that lies between the low water level and the vegetation limit on the backshore.

In Atlantic Canada, extensive coastal dunes including foredunes, parabolic dunes, and blowouts occur on the barrier islands and spit shorelines of New Brunswick, Prince Edward Island, and îles de la Madeleine, Quebec (Fig. 11). There are also numerous, smaller dunes along the coasts of Nova Scotia and Newfoundland associated with local sources of sand on otherwise predominantly rocky shorelines (McCann, 1990). Eolian dunes are also active on Sable Island (located off the coast of Nova Scotia) where high vegetated dunes and sand flats occur over most of the island.

According to McCann (1990) two factors indirectly influence the development and character of coastal dunes of the region. The first is a rising sea level along the east coast due to isostatic adjustments following glaciation (Quinlan and Beaumont, 1982). This has resulted in transgressive shoreline conditions in which beaches and associated sand dunes are being pushed landward. Predicted global climatic warming is anticipated to increase world sea levels due, primarily, to partial melting of the polar ice caps and an increase in the volume of ocean water as it expands with heating. In Atlantic Canada the rate of sea level rise will likely increase. Consequently, shoreline transgression may be more rapid. Shoreline transgression typically leads to erosion of dunes on coastal barriers, by wave overwash and landward retreat of the barrier (Nickling and Davidson-Arnott, 1990). On the bedrock mainland, rising sea levels may result in narrower beach width, reducing the sand supply and resulting in less eolian transport. On the barrier systems of New Brunswick and Prince Edward Island, increased rates in sea level rise could result in smaller, less well developed coastal dunes than at present due to sediment removal and overwash. Along the rockier shoreline regions such as Nova Scotia, sandy beach zones may be reduced in number and extent, thereby limiting eolian activity.

The second factor influencing Atlantic coastal dunes is the timing of the onset of spring. At present, the relatively late onset of spring typically inhibits new vegetation growth until mid-June (McCann, 1990). Also, the late spring period is

Figure 11.

Series of prograding foredune ridges, Dune du Sud, coast of îles de la Madeleine, Quebec (photo courtesy S.B. McCann. GSC 1995-067) relatively dry, further enhancing conditions for eolian sand transport. Inset B, Figure 1 indicates that, based on a doubling of atmospheric CO_2, the moderate temperature ecoclimatic region may expand into the existing maritime boreal regions of Nova Scotia, New Brunswick, and Newfoundland. With climate change, the onset of an earlier spring and longer growing season in Atlantic Canada may result in greater diversity of vegetation on coastal foredunes, possibly approximating that currently found on coastal dunes to the south such as in Cape Cod, Massachusetts. Whether this will result in substantial changes in eolian activity on coastal dunes in Atlantic Canada is uncertain, although a longer growing season may aid in stabilizing coastal dunes and possibly reduce the number of active blowouts and parabolic dunes.

An increased rate of sea level rise in Atlantic Canada may result in a reduced area for foredune development. In addition, a longer growing season may result in increased trapping of wind-blown sand on foredunes due to increased vegetation cover. The combined effect may result in less extensive foredunes than at present with a greater vegetation cover producing more stable dunes.

Great Lakes coastal dunes

Coastal dunes are common in the Great Lakes region (Fig. 8) of the cool temperate and boreal ecoclimatic regions and are found at the heads of small rocky coves, large arcuate bays, on top of low forelands, baymouth bars, or tombolos (Davidson, 1990). Martini (1981) has described the distribution and geomorphology of coastal dunes in Ontario. Around the Great Lakes, well developed foredunes exist along Lake Huron (Grand Bend) and Lake Ontario (Sandbanks and Outlet), with parabolic dunes present along the north shore of Lake Superior (Pukaskwa Park and Pic River), Georgian Bay, and Lake Huron (Wasaga Beach and Grand Bend). Blowouts are found superimposed on most dunes and are most prevalent on coastal regions of Georgian Bay and Lake Huron (north of Wasaga Beach and Sable Beach), and Lake Ontario (Sandbanks).

Great Lakes coastal dunes form two broad types along the shorelines. The most common type form behind the beach as foredunes while the second type form on top of coastal bluffs (cliff-top or perched dunes). As with other coastal foredunes the Great Lakes dunes are fed by sand deflated from the beach (Fig. 12). Therefore, beach sediment supply, beach width, and period of exposure to wind can alter the sediment supply to the foredunes.

With climate change, increased evapotranspiration in the Great Lakes region is expected to result in reduced discharge in rivers and decreased water levels of the lakes. Unlike the Atlantic coast, the Great Lakes shorelines could experience increased beach widths and progradation associated with decreasing lake levels. Sediment supply to foredunes may be increased during low levels due to a broader area of beach exposure, promoting greater rates of sand deflation (Olsen, 1958). In general, lower lake levels may lead to the formation of wider coastal foredunes (Nickling and Davidson-Arnott, 1990). However, the extent of eolian activity on these dunes is also a function of the wind regime, vegetation cover, and duration of snow-free months, all of which may be altered in the Great Lakes region by shifts towards cool temperate and moderate temperate ecoclimatic regions.

Cliff-top dunes, although less common than foredunes, form active dunes in the Great Lakes region. The most prominent in Canada are those in the Hepworth area along Lake Erie (Martini, 1981). As a point of interest, the largest active sand dunes in the Great Lakes region, those on the shores of Lake Michigan and Lake Superior in the State of Michigan (Marsh and Marsh, 1987), are cliff-top dunes. The sandy bluffs are continually eroded by slope processes and wave action at the base of the bluffs. Wind deflates sand inland from the eroding bluffs (Fig. 13). In contrast to foredunes, sand supply to the cliff-top dunes may be reduced by decreasing lake levels (Marsh and Marsh, 1987). Lower water levels are

Figure 12.

Migrating eolian sands around cottages on the eastern shore of Lake Huron (photo W.G. Nickling). GSC 1995-068 likely to reduce wave erosion of the bluff base and decrease the rate of bluff retreat. Consequently, vegetation will tend to stabilize exposures resulting in reduced sediment supply to the dunes.

In the past, logging, sand extraction, and recreation have disturbed many of the dunes on the Great Lakes. By the mid-1960s public concern for natural areas led to the increased protection of these areas. Today, provincial parks, national parks, and national wildlife areas incorporate some or all of 15 individual dunes systems in Ontario, protecting about 50% of the total area of Ontario's coastal dunes in special zones by official management plans (Davidson, 1990). Nevertheless, better resource management is still an issue in which a balance must be struck between the utilization and the protection of Great Lakes coastal dunes.

Arctic regions

The Arctic may be especially sensitive to climate change. All of the climate models predict that the greatest warming will occur in the higher, polar latitudes where average winter temperatures may increase from 4 to 16°C. Eolian processes are prevalent in the arctic regions of Canada with active sand dunes along riverways, coastal shorelines, and deltas. Active eolian features occur along the coastlines of Hudson Bay and James Bay, eolian sand sheets on Banks Island, and coastal dunes in the Tuktoyaktuk region of the western Arctic, and niveo-eolian deposits on Baffin Island (Filion and Morriset, 1983; Good and Bryant, 1985; McKenna Neuman and Gilbert, 1986; Martini, 1990; Ruz, 1993).

Although there are a large number of dune occurrences in the arctic regions of Canada, only a few are of significant size (exceeding 26 km^2 in area). These dunes are found in the vicinity of Fort Simpson in the Northwest Territories and have developed on sandy deltaic deposits. These dunes are presently covered with forest vegetation while the interdune areas are covered by swamps and bogs. It is unlikely that climate change, with potential changes to a more boreal ecoclimatic region, will re-initiate eolian activity in this area.

Several active eolian deposits occur in combination with strong ice-marginal (katabatic) winds, including those at the outlet of the Kaskawulsh Glacier/Slims River valley in Yukon Territory (Fig. 10; Nickling and Brazel, 1985) and in Pangnirtung Pass on Baffin Island (McKenna Neuman, 1990a). The local valley topography typically enhances the ice-marginal and storm winds in these areas. In the Slims River valley eolian activity including dust storms occurs primarily in summer when the low river stage exposes large areas of deposited silt and sand (Nickling, 1978). On Baffin Island, McKenna Neuman and Gilbert (1986) found that the deflation of Arctic sandar occurs predominantly during dry cold autumn and winter months, while adjacent eolian deposits are subject to rejuvenation year-round.

On Banks Island in the Beaufort Sea region of the Northwest Territories, fluvial deposits of ephemeral streams are subject to eolian activity during arid summer months (Good and Bryant, 1985) typically resulting in sand sheets and sand shadows. In this region, fluvial activity is generated annually by the release of winter precipitation during spring thaw. Eolian processes are also active in many other localities on Banks Island, including previously stabilized areas of eolian sands and where sandy deposits outcrop (Pissart et al., 1977).

There are also eolian dune deposits along the Mackenzie River valley, and the Tuktoyaktuk Peninsula along the Beaufort Sea, and lake shorelines (Y. Michaud, pers. comm., 1994; Ruz, 1993). The sand dunes of the Tuktoyaktuk Peninsula include low parabolic dunes (Mackay, 1963) and lakeshore dunes classified by Rampton (1988) as cliff-top dunes, although Ruz (1993) considers these dunes to be unique types of arctic coastal dunes specific to the thermokarst-affected transgressive coastline.

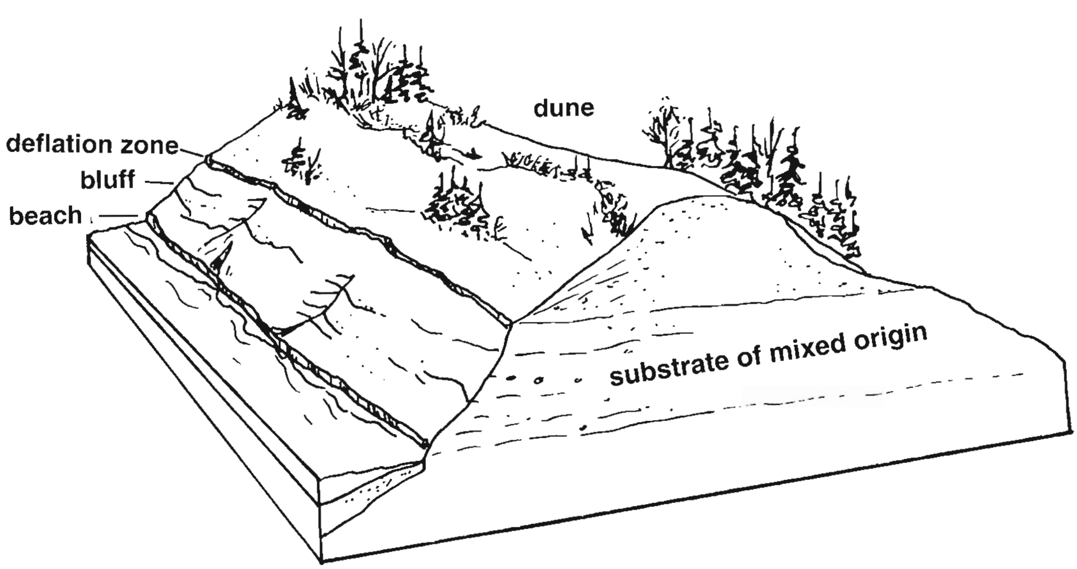


Figure 13. *Cliff-top dunes depicting deflation zone and lower bluff and beach.*

Climate change in the arctic regions is likely to affect most of the active eolian sand dunes. The source material for most sand dunes outlined above is derived primarily from fluvial deposits. Consequently, the eolian processes are probably most sensitive to changes in the hydrological regime affecting sediment supply to the dunes. If, for example, there is a decrease in the discharge of ephemeral streams associated with spring thaw, then there may be less reworking and deposition of sediment by streams resulting in a decrease in sediment supply for transport by wind. In areas along the margins of glaciers, fluvial discharge is also affected by the melting of glacial ice, particularly in summer. Therefore, some streams and rivers may have increased discharge in warmer months associated with increased ice melt. Similarly, sand dunes found along the coastal margins of the Tuktoyaktuk Peninsula may be affected by a change in the rate of marine transgression. However, eolian activity is further affected by soil moisture and vegetation, which will also be affected by potentially warmer temperatures in summer. Therefore, while arctic eolian processes are sensitive to climate change, increases in sand supply may be balanced by enhancement of stabilizing vegetation cover. Indeed, it is the total environment, with its systems and subsystems, that determines and controls eolian processes such that the potential magnitude of change in eolian activity in this and other regions is still largely unknown.

Wind erosion of agricultural soils

Throughout Canada, wind erosion is associated with agricultural soils. Although agriculture is a necessity, providing both employment and a large proportion of the gross national product, it can be viewed from the perspective of being the most serious anthropogenic disturbance of the natural surface. Present agricultural lands were once vegetated by either grasslands or forest, and under those conditions and the present climate they would be largely immune to wind erosion. However, clearing and subsequent tillage has made these soils more susceptible to deflation than adjacent nonagricultural surfaces, particularly during periods of drought (Fig. 14).

In most areas of Canada, wind erosion is much less severe than water erosion. However, at the regional or local scale, wind erosion of agricultural soils can be significant. Wind erosion is most severe in the Prairie Provinces where estimated deflation accounts for more than half of the total soil loss. The estimated soil loss by wind on the prairies is approximately 160 million tonnes per year (Sparrow, 1984). Economic losses to the Prairie farming community, based on nonrecoverable wheat production are also significant and have been estimated at approximately $327 million per year (Prairie Farm Rehabilitation Administration, 1983).

Wind erosion of agricultural soils is most severe and extensive when bare fields under low surface soil moisture conditions are exposed to wind. Soil losses due to wind erosion are also intensified by erosion-prone tillage and harvesting practices and inappropriate land management strategies including:

- not providing a vegetation or residue cover during months of high wind velocities and/or soil moisture deficits (particularly the practice of summer fallowing);
- excessive tillage that breaks down soil structure thereby reducing clodiness and surface roughness;
- tillage of light textured soils without invoking proper management strategies such as strip farming, maintaining a surface cover, etc.;
- reduction of soil organic matter content through decreasing inputs of crop residues, lack of grass/legume forage crop rotations, over-tillage, or deflation;
- removal of windbreaks and shelterbelts;
- increasing field size without use of strip farming or other erosion mitigating practices in erosion-prone areas.

In general, the above factors combine to increase the force of the wind at the surface and to increase the supply of transportable material through the reduction of soil structure and the removal of a protective cover or crust. Potential erodibility is further increased during drought periods because of the decreased vegetation cover and surface soil moisture.

Figure 14.

Wind eroded soil deposited along fence lines and ditches from a farm field in southern Saskatchewan (photo courtesy E.E. Wheaton). GSC 1995-069

Inset C (Fig. 1) shows the relative risk of wind erosion of bare, unprotected mineral soils in Canada. The map is derived from 1987 maps of wind erosion risk for the Prairie Provinces (Coote et al., 1987a, b; Coote and Padbury, 1987) and from a 1982 map for the rest of Canada (Coote et al., 1982). The wind erosion risk map does not take into account the protection provided by crop management within a cultivated area and is primarily a function of soil texture and climatic factors including existing wind conditions and surface soil available moisture as discussed previously (see section Wind erosion risk). Areas depicted in inset C (Fig. 1) should not been seen as areas of existing wind erosion, but as areas at risk to wind erosion if the underlying mineral soil is left bare and unprotected.

Within Canada, high wind erosion risk is most extensive in southern Saskatchewan and in parts of southeastern Alberta (inset C, Fig. 1). In general, the soils with severe wind erosion risk are the lighter textured soils developed on glaciofluvial and glaciolacustrine sediments. Soils developed on clayey textured sediments are at times also subject to wind erosion.

Although other regions of Canada generally have a moderate to low wind erosion risk, significant soil losses by wind have also been identified in several parts of southwestern Ontario where continuous corn cultivation is carried out on light textured soils (Nickling and FitzSimons, 1985). Reported areas of wind erosion in southwestern Ontario are shown in Figure 15. In almost all cases, the most extensive and severe wind erosion risk is confined to sandy loams and loams developed on glaciofluvial and coarse glaciolacustrine sediments. However, throughout southern Ontario, more localized areas of wind erosion have been identified and are frequently associated with excessive tillage and harvesting practices, which leaves insufficient residue, or the presence of organic soils. In the Maritime Provinces intensified production of row crops without sufficient residue or cover crops during the winter months has also resulted in increased wind erosion (Sparrow, 1984).

Wind erosion of prairie agricultural soils is frequently associated with dust storms, occurring most often in spring. On the basis of climatic data from 1977 to 1983, Wheaton and Chakravarti (1990) found that dust storms (with visibility reduced to 1 km or less at eye-level) are most frequent in south-central Saskatchewan where grain farming dominates. In this area there is an average annual frequency of more than 5 dust storms per year (Fig. 16). During the observation period, Regina recorded the greatest mean annual dust storm frequency with a maximum of 19 dust storms in 1981. In general, dust storm frequency decreases northward, falling to an average of less than 2 per year north of Prince Albert. Under present climatic conditions the northern agricultural portion of Saskatchewan has the lowest dust storm risk, the

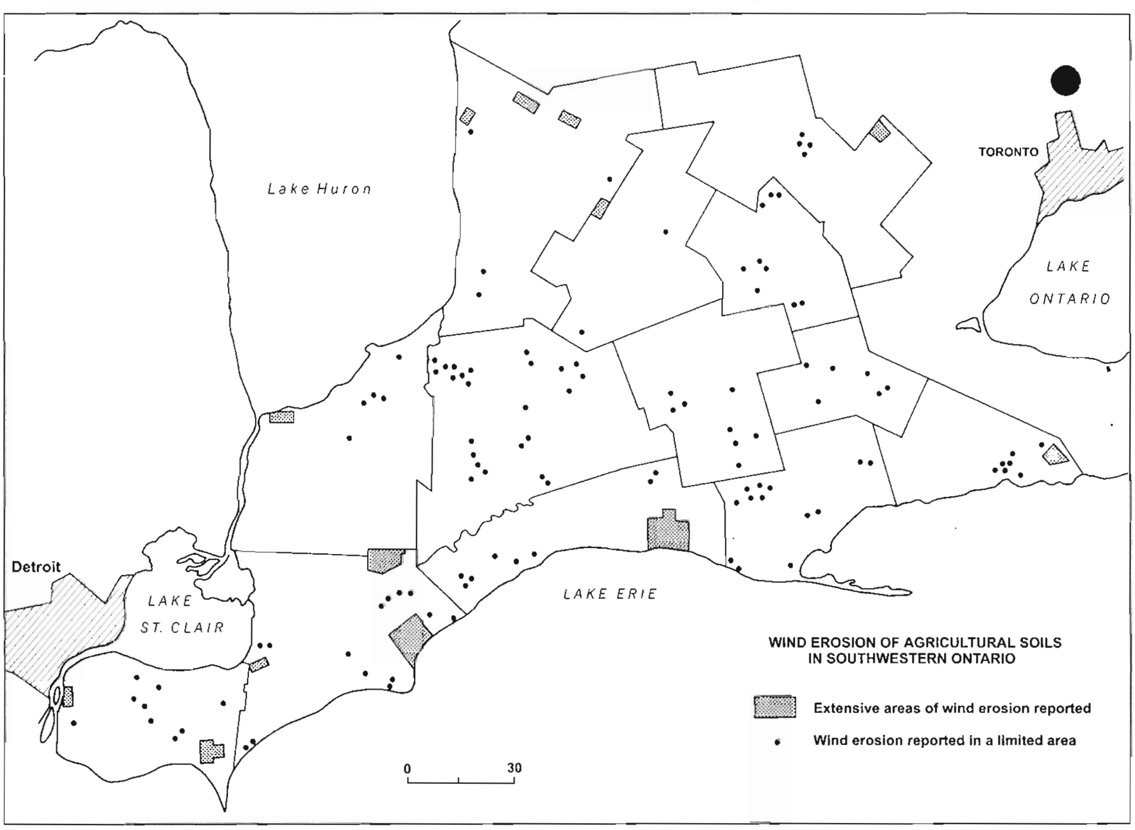


Figure 15. *Distribution of areas in southwestern Ontario affected by wind erosion (after Nickling and FitzSimons, 1985).*

southeast and central southwest has an intermediate risk, and the central south has the highest risk of dust storms and related loss of fertile topsoil (Wheaton and Chakravarti, 1990).

In the Prairie Provinces many farmers are actively attempting to reduce wind erosion through the implementation of control measures such as strip farming, adoption of no-till or other conservation tillage practices, reduction in summer fallowing, and the planting of wind breaks. As well, through the Prairie Farm Rehabilitation Administration (PFRA), the Canadian Government instituted the Permanent Cover Program that encourages farmers to take erosion-prone land out of annual production. Since the program's inception in 1989, over 400 000 hectares of land has been planted or committed to permanent cover.

Recent modelling studies indicate that many regions of Canada may experience significant changes in climatic conditions as a result of increased concentrations of atmospheric CO_2 and other greenhouse gases which may have serious ramifications for wind erosion on agricultural soils. The climate of the Prairie Provinces could be characterized by a significant increase in temperature in conjunction with modest increases in precipitation. The predicted increase in precipitation however, is expected to be offset by higher evapotranspiration rates resulting from the increased temperatures (Stewart et al., 1987). As a result, the climate would shift to a more drought-prone regime, with an increase in the length and frequency of droughts. Under these climatic scenarios, the return periods of drought and severe drought, as defined by the Palmer Drought Index, could be reduced by approximately half as shown in Table 2. However, Stewart et al. (1987) caution that, throughout the Prairies, a several-fold increase in drought frequency could occur if the precipitation levels predicted by the climatic models is not received. In this situation increased temperatures and evapotranspiration rates would create substantial soil moisture deficits resulting in decreased cover and crop residues, and increased potential for wind erosion.

Increases in wind erosion risk of bare, unprotected soil would be most severe in southern Saskatchewan and southern Alberta, particularly within the Palliser Triangle region. Although northern regions of Alberta and Saskatchewan would generally have minimal or minor increases in wind erosion risk, some areas such as the Peace River district may be more seriously affected because of the opening up of more agricultural land. Similar predictions may also be made for southeastern Manitoba.

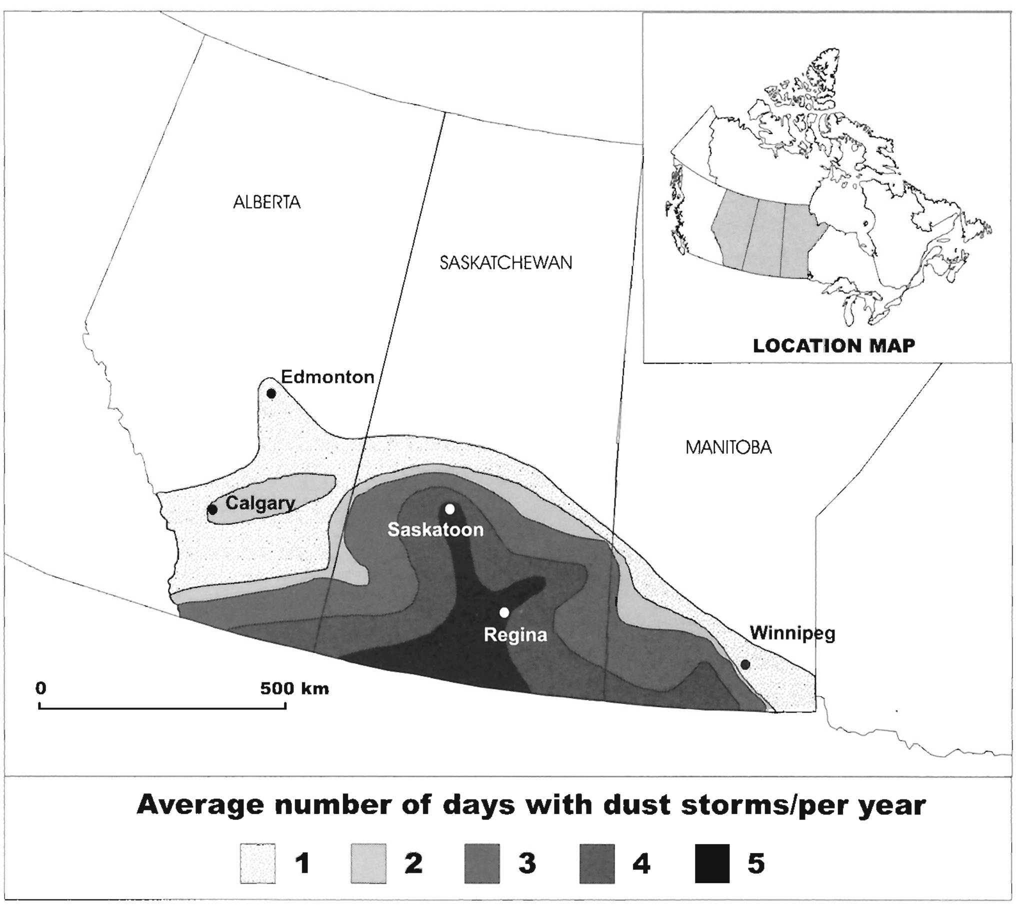


__Figure 16.__ Dust storm frequency in the Canadian Prairies (after Wheaton and Chakravarti, 1990).

Table 2. Return period of present and predicted drought conditions in Saskatchewan (after Stewart et al., 1987).

Drought Conditions	Return period (years)	
	From 1950-1982	$2xCO_2$ scenario
Drought	6.5-10	4-6
Severe drought	15-35	8.5-17.5

Smit (1987) presented a similar climatic scenario for southern Ontario based on the Goddard Institute of Space Studies General Circulation Model. He suggests that mean daytime temperatures during the growing season may increase by 1.5°C to 1.9°C depending on location, with increases in precipitation ranging from 105 mm to 150 mm. As in Western Canada, the effect of precipitation increase will be lost to increases in potential evapotranspiration ranging from 230 mm to 280 mm. In addition, Smit (1987) suggested that increased temperatures and soil moisture deficits will most likely be associated with increased climatic variability and potential for more frequent drought periods. Increased wind erosion risk will be most severe in southwestern Ontario on sandy soils where the highest soil moisture deficits are predicted. Increases may also be expected in central and northern Ontario if agricultural production expands northward due to increased temperatures.

Increased wind erosion of agricultural soils in Canada will have numerous ramifications. Wind erosion degrades soil quality through removal of nutrients and organic matter, leading to decreased crop productivity which further increases wind erosion potential. Blowing soil is abrasive and can damage buildings, machinery, and vegetation while dust storms hamper visibility to automobile and air traffic. As well, airborne nutrients, salts from dried lakes, and pesticides transported downwind may degrade water quality and aggravate human health problems (Government of Canada, 1991). Undoubtedly, climate change in Canada may bring about changes in agricultural land use and management practices. In some instances, new land will be opened for cultivation, potentially increasing wind erosion. On some existing agricultural land, changes in tillage techniques, harvesting, and management practices could mitigate against the effects of drought and wind erosion. In other circumstances, however, such as in the southern Prairies of Saskatchewan and Alberta, the climate may become too arid to support arable agriculture and land may be returned to grass cover, substantially diminishing wind erosion from present levels.

SENSITIVITY OF EOLIAN PROCESSES TO CLIMATE CHANGE

Under the proposed climatic scenario of a doubling of atmospheric CO_2 concentrations (Rizzo and Wiken, 1992) climate change in Canada will be accompanied by changes in the existing pattern of ecoclimatic regions. Cool temperate and moderate regions are predicted to increase along with grassland regions, while the boreal and subarctic regions are predicted to decline. In addition, under this scenario, the grasslands regions of southern Alberta and Saskatchewan may change to semidesert.

The changes in vegetation which accompany climate change may lead to changes in eolian activity by altering the protection provided by vegetation against wind erosion. In addition, changes in the amount and timing of precipitation, coupled with evapotranspiration changes due to alterations in temperature regimes, will affect the wind erosion susceptibility of bare soils by changing the surface soil moisture conditions. Other changes influencing eolian processes may include the nature and distribution of wind forces controlling the potential for sediment transport, lake and sea level changes affecting coastal dunes, river discharges influencing sediment supply, and changes to agricultural activity as affected by climatic conditions. Hence, the distribution and intensity of eolian processes in Canada are likely to change under this scenario of climate change.

Given the complexities of the response of eolian processes to climate change, a detailed assessment of the potential change in magnitude and distribution of eolian processes in Canada is not possible. However, a broad assessment of the sensitivity of eolian processes to climate change may be made based on the potential changes in the distribution of ecoclimatic regions in Canada. This is because changes in ecoclimatic regions are driven by changes in precipitation and temperature which cause changes in vegetation; (changes in vegetation are in part systematic of changes in soil moisture conditions). Vegetation cover and soil moisture conditions are two of the primary factors which control sand dune activity and erosion risk on bare, unprotected mineral soil. Effects such as changes in sediment supply due to adjustments in groundwater, lake or river levels, as well as agricultural practices mitigating against wind erosion, are not considered.

In the following analysis, eolian activity in dune areas is considered to be largely a function of vegetation cover and surface soil moisture conditions. The sensitivity of sand dunes to climate change is considered to be low in regions where changes in ecoclimatic regions result in vegetation cover or moisture conditions sufficient to suppress erosion. On agricultural soils, the level of risk on the bare, unprotected mineral soil is considered to be primarily a function of soil texture, wind regime, and surface soil moisture conditions. The sensitivity of wind erosion risk to climate change is considered to increase in those areas where the surface soil moisture availability is likely to be reduced due to changes in the distribution of ecoclimatic regions.

Figure 1 illustrates the sensitivity of dune areas to climate change in Canada. The figure is derived from the present sand dune occurrences in Canada (Fig. 8) and the predicted future ecoclimatic regions based on doubling of atmospheric CO_2 (Fig. 1, inset B). The sensitivity to climate change is defined on the basis of predicted changes in ecoclimatic regions. Level of climatic sensitivity is rated on a relative scale (severe, high, moderate, and low). The least sensitive (low) regions are those which are predicted to retain either sufficient vegetation cover or soil moisture under a CO_2 doubling scenario to inhibit regional eolian processes. These regions include the arctic, subarctic, boreal, cool temperate, transitional grassland, and those regions that change from boreal to moderate temperate under a CO_2 doubling scenerio. Sensitivity increases where a reduction in vegetation cover and/or a deterioration of surface soil moisture conditions results from precipitation reductions and increased temperatures. In this respect, climatic sensitivity is interpreted as moderate where boreal regions shift to grassland and where cool temperate regions shift to moderate temperate. High sensitivity is interpreted where grassland and moderate temperate regions remain "unchanged", as it is likely that these regions will be more arid rather than less so under a CO_2 doubling scenario. Severe sensitivity is interpreted where existing ecoclimatic regions change to semidesert.

The climatic sensitivity is low for most dune areas in Canada, including those in British Columbia, Quebec, Newfoundland-Labrador, Yukon Territory, and Northwest Territories as well as the northern reaches of Alberta, Saskatchewan, Manitoba, and Ontario. In general, vegetation cover and moisture conditions are sufficient to inhibit increased sensitivity of eolian processes. Dune sensitivity is severe, however, in southwestern Saskatchewan and southeastern Alberta due to the potential change in ecoclimatic regions from grassland to semidesert. The enclosed region of severe sensitivity roughly corresponds to the presently arid region of Canada identified as the Palliser Triangle. The associated decrease in precipitation and reduction in vegetation cover may increase the risk of sand dune reactivation in this region. Included in this region of severe sensitivity are the Great Sand Hills of Saskatchewan, as well as several smaller sand hills north of Maple Creek and west of Swift Current in Saskatchewan and around Lethbridge, Alberta. Other severely sensitive areas include the small sporadic dunes in south-central and southeastern Saskatchewan.

A region of high sensitivity extends across the northeastern margin of the area of severe sensitivity. This region corresponds to the present grassland regions of the prairies which may become more drought-prone under a doubling of atmospheric CO_2. To the north and east, dune sensitivity is moderate, corresponding to existing boreal forest regions which may change to grassland. A region of high sensitivity is also identified in southern Ontario where existing moderate temperate regions may become more drought-prone. In other regions of Ontario, Quebec, and the Maritimes, changes from cool temperate to moderate temperate ecoclimatic regions may induce moderate dune sensitivity. In Nova Scotia and Newfoundland, the change from maritime boreal to moderate temperate ecoclimatic regions is unlikely to increase dune sensitivity.

Figure 1 indicates the sensitivity of wind erosion risk of bare unprotected soils to climate change. The map was derived by overlaying the predicted future ecoclimatic regions (inset B) on the present wind erosion risk of bare, unprotected mineral soils in Canada (inset C). Unlike dune sensitivity, however, the sensitivity of wind erosion risk is not related to vegetation cover, since the surface is considered to be bare, but is primarily a function of surface moisture conditions. Vegetation cover is, however, a proxy indicator of surface soil moisture conditions so, indirectly, the predicted ecoclimatic regions map includes an element of the predicted change in soil moisture conditions. Figure 1 includes a table which is a sensitivity matrix, the upper row of the matrix indicates regions of most severe wind erosion risk under existing climatic conditions while the bottom row indicates regions of lowest risk. The columns identify estimated relative climatic sensitivity based on a doubling of CO_2. The leftmost column indicates regions of severe climatic sensitivity which is here defined as requiring a relatively small change in climate to push surface soil moisture conditions over a critical wind erosion risk threshold. The column on the far right indicates regions of low sensitivity (relatively large change required to reach a critical wind erosion risk threshold). Combined, the regions of most severe wind erosion risk and climatic sensitivity are identified by the top left corner of the matrix while the regions of lowest risk and sensitivity are identified by the bottom right corner of the matrix.

The sensitivity of wind erosion of agricultural soils to climate change in Canada parallels that of sand dune sensitivity. In general, the southern Prairies are identified as the most climatically sensitive, decreasing in sensitivity northward. Southern Ontario and portions of the Maritimes, including Prince Edward Island are identified as being moderately sensitive, with some highly sensitive regions in the extreme southern portion of Ontario. Other regions of the Maritimes, northern Quebec and Ontario, as well as northwestern Alberta and British Colombia, are identified as having a low sensitivity to climate change.

Variations in soil types produce differences in wind erosion risk within specific regions of climatic sensitivity. In particular, almost half of the total area shown at risk to wind erosion in Figure 1 has a high to severe climatic sensitivity. Furthermore, while over half of the total area may be classified as having a low present wind erosion risk, approximately 20% has a high to severe risk of wind erosion. Nearly 80% of this latter area is classified as having high to severe climatic sensitivity, indicating that the regions with a highest proportion of soils at risk to wind erosion also tend to be in climatically sensitive areas. In particular, over 40% of the region of southern Alberta and Saskatchewan identified as the most climatically sensitive in Canada has a high to severe wind erosion risk. In contrast, less than 10% of the total area in Canada with moderate to low climatic sensitivity has a high to severe wind erosion risk.

In summary, while a high proportion of agricultural land in Canada has a low present wind erosion risk, those areas of highest risk also tend to be in the most climatically sensitive regions. In particular, the southernmost regions of Alberta and Saskatchewan are the most climatically sensitive (wind erosion risk could be altered critical by a small climatic change) and tend to have a high proportion of soils presently at risk to wind erosion. The sensitivity of wind erosion of agricultural soils follows a similar trend to sand dunes in Canada, being most sensitive in the southern Prairies and decreasing northward. In addition, southern Ontario and portions of the Maritimes including Prince Edward Island are also identified as having moderate to high climatic sensitivity.

The sensitivity of sand dunes and wind erosion risk to climate change in Canada shown on these maps is speculative, and is based on only one possible scenario of climate change resulting from a doubling of atmospheric CO_2 concentrations. In addition, the basis for the climatic sensitivity of eolian processes has been greatly simplified to consider primarily changes in surface soil moisture conditions and vegetation cover. As a consequence, anomalous areas exist such as the Athabasca sand dunes, which are active today in a region of comparatively low climatic sensitivity. Nevertheless, these maps may be used to identify regions which are potentially at risk to enhanced eolian activity resulting from climate change in Canada.

CONCLUSIONS

Eolian processes in Canada have been active throughout geological time and continue to operate today. The extent and level of eolian and of all geomorphic modifications is in part a function of past and present climatic conditions. Eolian processes are a result of the complex interaction of sediment supply, nature and distribution of wind forces, as well as other natural and anthropogenic factors.

Climate change associated with increased CO_2 concentrations will affect eolian processes directly, through alterations in temperature, moisture, and wind regimes and indirectly, by altering the nature of sediment transport and supply. In particular, changes in vegetation cover, lake and sea levels, river discharges, as well as urban and agricultural activity will alter the magnitude and distribution of eolian processes in Canada.

The sensitivity of sand dunes and the wind erosion risk of bare, unprotected soils to climate change in Canada varies regionally. The most sensitive regions are those in which vegetation cover may be reduced sufficiently to permit remobilization of sediment and where alterations in the temperature and moisture regimes may induce drought. The complex interactions of direct and indirect effects of climate change makes current assessment of the potential change in the magnitude and distribution of wind erosion in Canada difficult. The present assessment of the sensitivity of eolian processes to climate change represents a first step to understanding the potential impact of climate change on eolian processes in Canada.

ACKNOWLEDGMENTS

The authors are grateful to those who contributed to this bulletin. Map production by Brian Morber and illustrations by Leslie Nutt and Marie Puddister, Department of Geography, University of Guelph, were greatly appreciated. Brian McCann, Department of Geography, McMaster University; Elaine Wheaton, Saskatchewan Research Council; and Derald Smith, Department of Geography, University of Calgary kindly donated photographs; while Wendy Hales provided additional sand dune occurrence in formation for Nova Scotia. Dick Coote and Glen Padbury, Centre for Land and Biological Resources Research, Agriculture Canada, provided useful details and access to preliminary wind erosion risk maps. The text benefitted from critical readings by Peter David, Département de Géologie, Université de Montréal, and Glen Padbury, and through discussions and editorial changes provided by Bob Fulton.

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APPENDIX

Wind erosion mechanics

Principal factors

The wind profile

The action of wind blowing over the surface of the Earth imparts a force on particles lying on the ground. When air blows across most natural surfaces the flow is typically turbulent and is characterized by eddies of varying size moving with different speeds and directions. As a result of frictional effects, the wind speed near the surface is reduced (Fig. A-1A). If a graph of wind speed against the logarithm of height is drawn (Fig. A-1B) the relationship is typically linear and can be described by the Prandtl-von Karman equation:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{z}{z_o} \quad (1)$$

where u is the velocity at height z, z_o is the characteristic roughness length or height of the surface, κ is von Karman's constant ($\approx$0.4), and u_* is the friction or shear velocity.

For sand surfaces, z_o has been found by numerous investigators to be approximately equal to 1/30 of the mean particle diameter, but also varies with the shape and average distance between individual particles or other roughness elements.

The shear velocity (u_*) is proportional to the slope of the wind velocity profile when plotted with a logarithmic height scale. It is an indirect measure of the wind force or shear stress at the surface and represents the energy available to entrain and transport sediment (Fig. A-1B).

Forces acting on particles at the bed

If one considers a sand particle at rest on the surface of a loose sand bed over which a strong air stream is blowing, several forces are found to be acting on the particle (Fig. A-2). In general, these forces can be divided into two groups: 1) those that tend to raise the particle from the bed including drag, lift, and moment forces; and 2) those that tend to hold the particle in place such as weight and interparticle forces including moisture films or other bonding agents. The drag and lift forces, as well as the resultant moments, are caused by the air flow over and around the exposed particles.

If the wind speed is sufficiently high the combined drag and lift forces will just overcome the retardant weight and frictional forces then the particle will be entrained into the air stream.

Particle threshold

On the basis of theoretical considerations and empirical observations, Bagnold (1941) developed an expression to define the threshold shear velocity (u_{*t}) at which the movement of loose particles begins:

$$u_{*t} = A \sqrt{\frac{(\sigma - \rho)}{\rho} gd} \quad (2)$$

where σ and ρ are the particle and air densities respectively, g is the acceleration due to gravity, d is particle diameter and A is an empirical coefficient that has a value of approximately 0.1 for grains larger than approximately 0.08 mm. For these larger grains, the threshold shear velocity (u_{*t}) increases linearly with the square root of grain diameter. In this

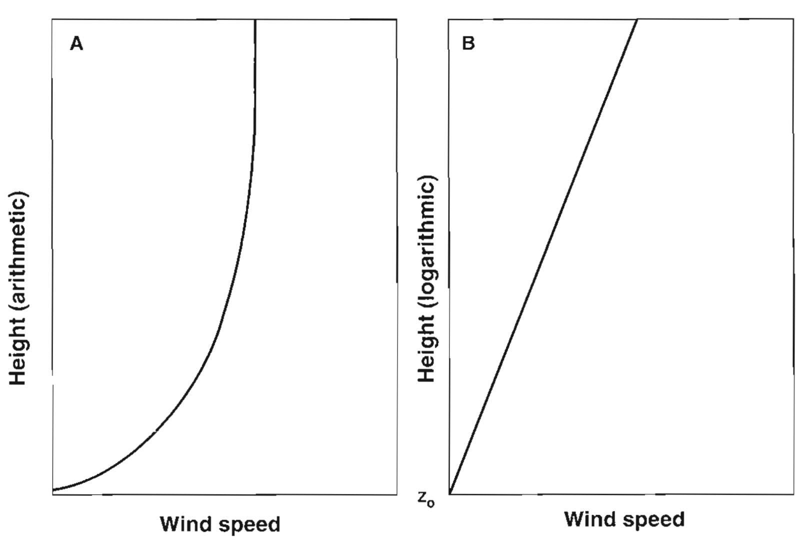

Figure A-1.

***A)** The wind profile. **B)** The wind profile plotted with the logarithm of height.*

situation, the relatively large grains are more susceptible to entrainment because they protrude higher into the air stream than the general surface. In contrast, particles <0.08 mm lie within a slower moving layer of air existing close to the bed (viscous sublayer) and these grains are not as readily entrained.

Once the threshold shear velocity has been reached, stationary particles begin to roll (creep) or bounce (saltate) downstream because of the direct pressure of the wind. During the downwind movement the momentum of the saltating grains increases before they fall back to the surface. On striking the surface, the moving particles may bounce off other grains and become re-entrained into the airstream or embedded in the surface. In both cases, momentum is transferred to the surface through the disturbance of one or more stationary grains. As a result, other particles are ejected into the airstream at shear velocities lower than that required to move stationary grains by airflow alone. This additional, lower threshold has been termed the dynamic or impact threshold (Bagnold, 1941). Wind tunnel experiments by Bagnold (1941) indicate that the dynamic impact threshold for a given sediment follows the same square root function as the fluid threshold but with a value of 0.08 instead of 0.1 for the coefficient A.

Modes of transport

Several distinct modes of particle transport can take place depending, primarily, on the grain size (Fig. A-3). Very small particles (less than 0.02 mm) are usually transported in suspension and kept aloft for long distances by the turbulent eddies of the wind. Larger, sand-sized, particles (0.07 to 0.5 mm) move downwind in a series of bounces or hops in a process termed saltation. In true saltation, particles are ejected into the air stream at fairly steep angles. After reaching some maximum height, they are carried by the wind in relatively smooth trajectories, falling back to the surface where they impact and bounce back into the air or become imbedded in the surface (Fig A-3). Larger or less exposed particles (larger than 0.5 mm) are pushed or rolled along the surface primarily by the impact of salting grains in surface creep. Figure A-3 also depicts two intermediate modes of transport, termed modified saltation and short term suspension, representing transport of grains through combined modes. Gillette (1977) and others have also found that very small particles, having the potential to be transported in suspension, are normally not entrained into the air stream by the direct force of the wind. Rather, these small particles are primarily ejected into the air by the bombardment of grains moving in saltation and creep.

Bagnold (1941), from his study of dune sands, found that the greatest proportion of the sediment transport was in saltation, with creep representing approximately 25% of the total transport rate. Subsequent investigations (e.g. Chepil, 1945; Williams, 1964; Gillette and Walker, 1974; Nickling, 1978; Finlan, 1987) have found that the proportion of sediment transported in creep, saltation, and suspension can vary significantly depending on the shape and size of the eroding sediment, surface roughness characteristics, and vegetative cover.

Transport equations

Bagnold (1941) was the first to develop a mathematical expression to account for the quantity of sand transported as a function of the shear stress exerted by wind. From theoretical

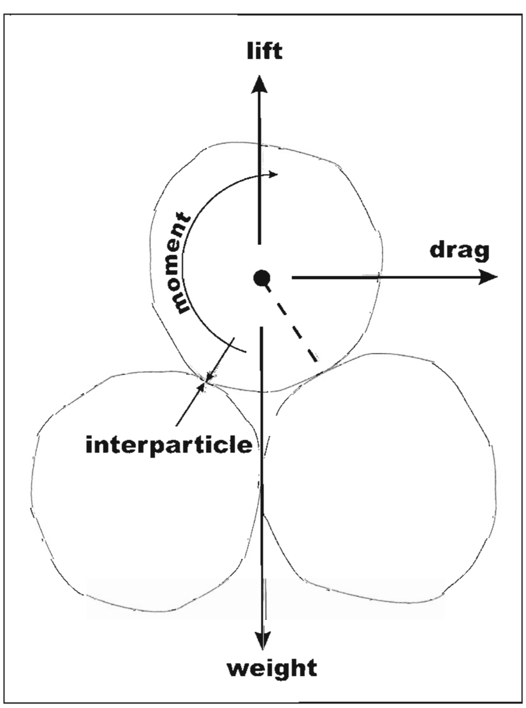

Figure A-2.

Forces on a particle at the bed.

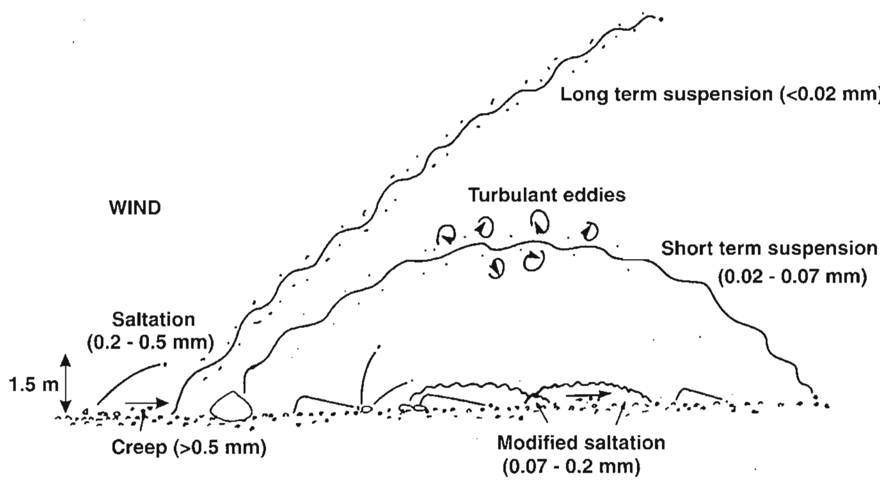

Figure A-3.

Modes of particle transport as a function of grain size.

considerations in conjunction with field observations and detailed wind tunnel testing he found that the sediment transport mass flux in saltation and creep (q) could be defined by:

$$q = C_s \sqrt{\frac{D_m}{D_s}} \left(\frac{\rho}{g}\right) (u_*)^3 \qquad (3)$$

where (D_m/D_s) is the ratio of the mean size of a given sand to that of a 'standard' 0.25 mm sand. The coefficient C_S is a sorting coefficient and has the following values:

1.5 for nearly uniform sand

1.8 for naturally graded sand

2.8 for poorly sorted sand

3.5 for a pebbly surface

Thus, holding other factors constant, the sediment flux, q, increases from a minimum for nearly uniform sand to somewhat higher values for more poorly sorted sands and obtaining a maximum value over a pebble surface. Higher sediment transport rates occur over pebble surfaces because of the more elastic collision between the saltating grains and the hard surfaces of the pebbles. Subsequent to Bagnold's (1941) work, other investigators have developed both theoretical and empirical equations to describe the transport of sediment by wind (Kawamura, 1951; Zingg, 1953; Owen, 1964; Lad and Lad, 1978). These equations, although frequently derived in different ways and from different points of view, are similar in general form to that proposed by Bagnold (1941) but can predict significantly different sediment transport rates.