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The usual assumption of alignment of the surface stress and surface wind vector was re-examined. This assumption appears to break down with significant temperature advection. This problem was examined in terms of tower data collected in the coastal zone by the Risoe National Laboratory (Denmark).

The usual formulation of the surface heat flux in models is inconsistent in that the aerodynamic temperature required for Monin-Okukhov similarity theory is replaced by the surface radiation temperature. The aerodynamic temperature is not readily available and numerous empirical fixes have been suggested to close the system. The approach here circumvents these problems by relating the evaporative fraction to remotely sensed information using data from the Boreal Ecosystem-Atmosphere Study and the California Ozone Deposition Experiment.

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Contents

Preface

This AASERT (Augmentation Awards for Science and Engineering Research Training) grant was associated with Phillips Laboratory (ASD/APB, Hanscom AFB, MA 01731) contract No. F19628-91-K-0002, 'Marine Boundary-Layer Parameterizations for Large–Scale Models' (12 Feb 91 - 15 Apr 94), and subsequently with contract No. F19628-94-K-0001, 'Subgrid Variability and Parameterizations of Coastal Zone Meteorology for Large-Scale Models' (15 Apr 94 - 30 Sep 95). The long term goal of the parent contracts was to improve the parameterization of subgrid scale fluxes in large-scale numerical weather prediction models.

1. Computation of surface fluxes

Introduction

Verification of model predictions is constrained by our limited ability to measure surface fluxes. One of the problems is extracting the turbulent flux from time series which categorically include mesoscale motions on a variety of scales, including scales which are only slightly larger than turbulent scales. "Background" mesoscale motions occur in all of the numerous data sets which we have examined. Attempts to filter out the mesoscale motion alter the computed turbulent flux. Different investigators analyzing the same data will often arrive at different flux values due to different techniques of removing the mesoscale motion (detrending, filtering). One of the difficulties is that both the turbulence and mesoscale motions are not periodic and contain sudden changes. As a result, the usual decomposition techniques fail to cleanly separate turbulence and mesoscale motions. As a result, the computed turbulent fluxes are contaminated. The three studies outlined in this chapter improve the decomposition between turbulent and mesoscale motions by basing the decomposition on local basis sets (including but not limited to wavelets) which themselves contain sharp edges. This allows better estimates of the fluxes for model verification, particularly in cases of significant nonstationarity.

1a. An Adaptive Decomposition: Application to Turbulence[1]

Geophysical time series generally consist of physically distinct modes of variation, each occurring on a subrange of scales which depend on spatial position and time. Conventional decomposition or filtering techniques divide the time series according to scales which are constant in space and time. In this study, distinct modes were isolated using a piece-wise constant (Haar wavelet) decomposition which allows the scales defining a particular mode to vary with record position. With this approach sampled covariances are completely and orthogonally decomposed. Partitioning the flow in this manner allows assessment of the relative contributions of the different modes to traditional statistics.

The turbulence data analyzed in this study have been partitioned into four modes of variation. Each mode is defined locally in terms of an upper and lower cutoff scale. The cutoff scales for the two larger scale modes are specified to be constant with respect to record position. The scale separating the two smaller scale modes varies with position according to the local maxima in the spatial distribution of momentum flux. Using a wavelet decomposition to examine the spatial or temporal distribution of the scale dependent flux is a promising approach for distinguishing between distinct physical modes of variation.

Adapting the decomposition to the spatial distribution of momentum flux leads to an improvement in the small scale partitioning as interpreted in terms of globally averaged

[1] from: Howell, J. F. and L. Mahrt, 1994: An adaptive decomposition: application to turbulence. In: *Wavelets in Geophysics*, E. Foufoula-Georgiou and P. Kumar, Eds., Academic Press, 107-128.

statistics. The spatial dependence of the cutoff scale allows the computed transport mode to capture more of the momentum flux; some of the flux occurring on scales traditionally included as fine scale structure is now more correctly included in the transport mode. For the transport mode, the gradients in the longitudinal wind component are negatively skewed in the downstream direction, which verifies that this mode is primarily shear driven. If a constant cutoff scale were used, the skewness of the gradients in the longitudinal wind for the main transporting motions would be only -0.230. After the additional small scale variations are included by varying the cutoff scale, the gradient skewness is -0.846. This change is a result of further resolving the microfronts associated with momentum transport. Moreover, the adaptive step leading to the spatially varying cutoff scale reduces the u-w correlation for the computed fine scale structure leading to a physically more pure decomposition.

Application of the adaptive technique to other geophysical time series requires that the variable cutoff scale be posed in terms of the physical process of interest. The physics of the decomposition might also be posed in terms of sudden changes of a quantity associated with larger scale variations. With traditional filtering, for example, sudden climatic changes, sharp frontal boundaries, or any near discontinuities in the time series which lead to large scale changes will be partially partitioned into the small scale part; the corresponding low pass filtered signal will include only a smoothed version of the sharp changes. The adaptive decomposition applied here can be constructed to include sharp changes in the larger scale part of the signal, avoiding undue smoothing. The basic goal of the adaptive technique is to partition the flow according to the physics when the subrange of scales describing a given physical mode varies spatially or temporally. Since the present approach partitions the original time series into separate time series for each mode, the coherent structures associated with a particular physical mode can in turn be analyzed.

1b. Identifying Sudden Changes in Data[2]

This work describes a simpler method for locating sudden changes in mean data values. Positions of sudden changes are boundaries of variable-width blocks of data. These boundaries could correspond to synoptic frontal boundaries, the downstream edge of a wind gust, or, generally, any anomalous change in a locally averaged quantity. The algorithm described here is applied to artificial signals, century-long records of precipitation, and atmospheric turbulence data.

Sharp boundaries or sudden changes occur regularly in geophysical data and can be important indicators. For example, a position of a sudden change in sea surface or air temperature may separate different phases of a synoptic-scale wave, or the position of a sudden change in the wind speed may separate different flux regimes. Such positions can, in turn, be used to divide a record of data into more homogeneous subrecords. Homogeneity is a basic assumption in, for example, surface layer similarity theory.

When a record is divided into constant-width blocks the positions of the blocks are fixed by the record length. By allowing the block widths to vary, the position of a given block

[2] from: Howell, J. F., 1995: Identifying sudden changes in data. *Monthly Weather Review*, **123**, 1207-1212.

can be determined by the local variations in the data. This approach is taken by the variable block averaging (VBA) filter[3]. This filter positions the data blocks such that the boundaries of the blocks coincide with any sudden changes or rapid transitions in mean data values.

As an application example, the filter was applied to century-long records of monthly precipitation at four different sites in Oregon. At these four sites, anomalous mean precipitation values increased during the latter half of the century. This increase was identified by dividing the precipitation records into 5-year wet anomalies and 5-year dry anomalies. In general, the VBA filter can be used to divide a record of data into more homogeneous, or more stationary subrecords. More homogeneous samples admit to simpler physical theories. The VBA filter was also applied to 11.5 hours of turbulence data measured 10 m above a shallow sea. The time series was divided into 12 variable-width data blocks according to the 1-h variations in the horizontal wind speed. A drag coefficient was calculated for each block. Compared to using 12 nonoverlapping constant-width blocks, the variance in the block-averaged wind speeds was greater, while the values of the drag coefficients varied less when using the variable-width blocks.

1c. Multiresolution Flux Decomposition[4]

Multiresolution cospectra are constructed by orthogonally decomposing the flow into averages using different averaging lengths. This simple decomposition formally satisfies Reynolds averaging for each averaging length and therefore leads to cospectra that are naturally suited for the study of turbulent fluxes. For the analyzed atmospheric turbulence data, the dependence of multiresolution cospectra on averaging length is qualitatively similar to the dependence of Fourier cospectra on wavelength, though the two cospectra retrieve different information. Fourier cospectra generally peak at a wavelength that is larger than the averaging length corresponding to the peak in multiresolution cospectra.

The *sample variance* associated with calculating a multiresolution cospectrum value leads to an estimation of the random sampling error. Consequently, confidence intervals naturally accompany multiresolution cospectra. Significant phase errors or scale aliasing problems for short records can be reduced by applying the spatially nonorthogonal version of the decomposition.

For stationary conditions, variability of the flux within the first flight pass serves as a useful estimate of flux variability during subsequent passes. Therefore, the number of repeat flight passes needed to reduce the relative error to a specified value can be predicted from the flux variability within the first pass. Estimates of the relative random sampling error, and the required record lengths to reduce that error to a specified level

[3] The VBA algorithm as F77 computer code (vba.f) is available via anonymous ftp (at least through the year 2000) on ats.orst.edu (IP=128.193.120.19), under directory pub/howell. A sample driver program and some documentation are also included in the vba.f file.

[4] from: Howell, J. F. and L. Mahrt, 1997: Multiresolution Flux Decomposition. *Boundary-Layer Meteorology*, to appear.

can be readily updated in real time with this approach.

For heterogeneous (or nonstationary) records, the flux at larger scales can be significant but characterized by large sampling errors. Since the choice of the averaging length (cutoff scale) for defining the largest scales included in the turbulence flux calculation is uncertain, the flux calculation becomes ambiguous (Sun et al, 1996). Generating the multiresolution flux decomposition is a direct approach for evaluating the dependence of the flux on the Reynolds averaging length.

References

Sun, J., J. Howell, S. K. Esbensen, L. Mahrt, C. M. Greb, R. Grossman, and M. A. LeMone, 1996: Scale dependence of air-sea fluxes over the western equatorial Pacific. *Journal of the Atmospheric Sciences*, **53**, 2997-3012.

2. Cross Stream Surface Wind Stresses[5]

In this study, cross-wind surface stresses have been examined using data from the Risoe Air-Sea Interaction Experiment (RASEX; Danish coast, spring 1994). Modelling the observed (cross stream) stresses may be helpful in the formulation of more accurate numerical models and remote sensing retrieval algorithms. It has been theorized that the height dependence of the horizontal velocity shear associated with longitudinal temperature advection combined with downward non-local mixing of momentum can lead to a systematic nonvanishing cross stream momentum flux near the surface (Geernaert, 1988). Steps have been made here to augment surface layer similarity theory to include this "Geernaert effect" and to test the theory using 10 m tower observations.

For the data analyzed in this study, the effect of the thermal wind does not appear to be an important factor in determining the cross stream stresses. Several reasons why the theory did not work in this case are (1) errors in the flux estimates, (2) inability to predict the thermal wind from tower data, and (3) other physics needs to be included. Multiple physical mechanisms may be required to more fully explain the variance in the cross stream stress.

The surface layer wind stress is observed to often rotate more than the simultaneous rotation of the wind vector. This observation is based on approximately two hour subrecord averages of the wind and stress directions. This relationship is consistent with non-local mixing of momentum combined with a rotating wind field where the maximum rotation is above the surface layer.

In the context of the present model, such a rotating wind field could be associated with the passage of a mesoscale temperature anomaly where the pressure perturbation

[5] from: Howell, J. F., 1995: Chapter 5. Cross Stream Surface Wind Stresses. In: Sudden changes in local mean values demarcate geophysical regimes, PhD thesis, College of Oceanic and Atmospheric Sciences, Oregon State University, 143 pp.

increases with increasing height. The vertical profile of momentum in this conceptual model changes depending on the phase of the overlying anomaly. This is due to the temperature advection that changes from the leading edge to the trailing edge of a temperature anomaly. The changing momentum profile combined with the rotating wind vector aloft can lead to a surface stress that rotates more than the surface wind vector due to vertical mixing. The passage of a two-dimensional mesoscale vortex, whether or not geostrophic balance holds, may have similar effects.

For future research, the theories reviewed here should be tested against observations from different platforms. The influence of the momentum above the surface layer on the surface layer stress direction needs to be firmly validated. Also, the formulation of the cross stream momentum flux needs to be extended to include Ekman cross-isobar flow and the interaction of the wind stress with surface waves and surface currents.

References

Geernaert, G. L., 1988: Measurements of the angle between the wind vector and wind stress vector in the surface layer over the North Sea. *Journal of Geophysical Research*, **93**, 8215-8220.

3. Estimation of area averaged evapotranspiration[6]

Toward the goal of predicting area-averaged evapotranspiration suitable for comparisons with grid averaged fluxes implied by numerical models, the evaporative fraction has been modelled in terms of remotely sensed variables and air temperature. For the Boreal Ecosystem-Atmosphere Study (BOREAS; summer 1994, central Canadian boreal forest) and the California Ozone Deposition Experiment (CODE; summer 1992, San Joaquin Valley) data sets, the spatial variation of the evaporative fraction is much greater than the day-to-day variation at a given location. The day-to-day variation of the evaporative fraction has been formulated in terms of the air-surface temperature difference and zenith angle. The zenith angle accounts for the influence of shaded ground on the remotely sensed surface radiation temperature.

The spatial variation is incorporated by classifying the surface into bare soil, agricultural areas, forests and water surfaces. This classification is implemented in terms of remotely sensed red and near infrared reflectances which are superior to albedo and Normalized Differential Vegetation Index (NDVI) as discriminators. Alternatively, such division could be carried out with existing landuse data. Even after such classification, the evaporative fraction sometimes varies significantly within a class. Although the red reflectance sometimes performs better than the NDVI and albedo, particularly for forests, NDVI and albedo are more available for routine practical daily application and therefore are used for the within class models. The evaporation over water surfaces is modelled directly in terms of the bulk aerodynamic method.

[6] from: Mahrt, L., K. Kotwica, J. Sun, J. I. MacPherson, and R. Desjardins, 1997: Estimation of area averaged evapotranspiration. *Boundary-Layer Meteorology*, to be submitted.

To estimate the area averaged evaporation, the evaporative fraction is predicted with the class models and then converted to evapotranspiration given observations of net radiation. This output is combined with the prediction over the water surfaces to form the area averaged evapotranspiration. Models based on evaporative fraction normalized by downward solar radiation perform as well as those normalized by net radiation suggesting that the input information can be simplified without reducing model accuracy.

Applying the model to aircraft grid flight patterns successfully predicts the area-averaged surface moisture flux for the data in this study. However, the generality of the above approach is not known and data for low sun angles is not available. The analysis also needs to be extended to more surface types such as semi-arid conditions, tropical rain forests and snow covered conditions to generalize this model for global application. This study used 30 m air temperature and winds observed by the aircraft. Application of the above methods with satellite data would require use of synoptic winds and air temperature.

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Graduate students[7]

Dr. James Howell was supported from 1 January 1994 through 18 December 1995 under this AASERT grant and completed a PhD thesis in December 1995 (see the 'thesis prepared' citation below). The results of his research form the basis for several papers published in refereed journals (described in chapter 1 above; see references 1, 2, and 3 in the 'articles prepared' list below). Chapter 5 of his thesis has important implications in modeling surface stress (described in chapter 2 above; not yet published). Dr. Howell now holds a prestigious Postdoctoral Fellow in the Advanced Study Program at the National Center for Atmospheric Research in Boulder, Colorado.

Mr. Kotwica was supported from 1 April 1995 through 12 December 1996 and has analyzed aircraft data sets towards the goal of improving (subgrid) surface flux modeling over nonhomogeneous terrain. Results of this research are being prepared for publication (described in chapter 3 above; see reference 4 in the 'articles prepared' list below). Mr. Kotwica successfully defended his Master's thesis in November 1996 in the area of applied climatology. He thesis work was separate from his work for the AASERT Grant.

Thesis

Howell, J. F., 1995: Sudden changes in local mean values demarcate geophysical regimes. PhD thesis, College of Oceanic and Atmospheric Sciences, Oregon State University, 143 pp.

Articles

1. Howell, J. F. and L. Mahrt, 1994: An adaptive decomposition: application to turbulence. In: *Wavelets in Geophysics*, E. Foufoula-Georgiou and P. Kumar, Eds., Academic Press, 107-128.

2. Howell, J. F., 1995: Identifying sudden changes in data. *Monthly Weather Review*, **123**, 1207-1212.

3. Howell, J. F. and L. Mahrt, 1997: Multiresolution Flux Decomposition. *Boundary-Layer Meteorology*, to appear.

4. Mahrt, L., K. Kotwica, J. Sun, J. I. MacPherson, and R. Desjardins, 1997: Estimation of area averaged evapotranspiration. *Boundary-Layer Meteorology*, to be submitted.

[7] Support was 0.5 FTE during the academic year, and 1.0 FTE during summer months (1 July - 15 September).