Inclusion of non-stationarity of the wind and wave fields in the bulk formula for surface fluxes: A new direction

FINAL REPORT

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Contract Number: N000141912469

1. Motivation

1) The heat and momentum flux in coastal zones and inland seas are often fetch dependent. The vertical divergence of the stress and the heat flux in such flows may be large near the surface such that fluxes measured at 10 m, for example, can significantly underestimate the surface fluxes. This underestimation leads to mis-calibration of similarity theory. The relative flux divergence may be particularly large in thin fetch-dependent boundary-layers.

2) The absence of long data sets has often made separation of the effects of stability and wave state/wind direction from observations difficult. Even offshore fixed tower sites seldom have more than a few months of flux measurements.

3) The literature disagrees on the overall importance of wave state and further analysis requires explicit information on wave state.

4) The general neglect of the impact of non-stationarity ignores important non-equilibrium interactions between the surface roughness, the stress, and the wind field.

The completed research has met these goals to various degrees and has also expanded into new areas (parts of Section 4) that were strongly suggested by the research.

2. The influence of non-stationarity on the drag coefficient.

Mahrt et al (2020) analyzed six years of 10-m flux data from the Oestergarnsholm site in the Baltic for near-neutral stability to examine the general enhancement of the momentum flux and drag coefficient due to the non-stationarity of the wind field. For long fetches, a few hundred km or more, the variation of the drag coefficient for semi-stationary conditions is well approximated by existing formulations, *excluding frontal events and low-wind speeds.*

Although individual non-stationary motions and their impact on the stress seem unpredictable, the non-stationarity systematically augments the stress when averaged over many cases. The non-stationary measurements were partitioned into sub-classes of short-term flow acceleration and deceleration on time scales of tens of minutes. Based on compositing the events, the drag coefficient is augmented in the initial stages of acceleration periods and during the later stages of deceleration periods.

The increase of the drag coefficient during the initial acceleration stage is consistent with initial generation of short waves (Fig. 1). The lagged increase of the drag coefficient during deceleration is consistent with the finite adjustment time required for the stress to decay in response to the flow deceleration. The stress has memory of previous higher wind speeds. At the same time, the response of the stress to the non-stationarity may be more complex than a single effect. These frontal structures are embedded in a region of generally enhanced drag coefficient. Modeling extreme events requires modification of the usual formulations of the drag coefficient. In addition to underestimating the drag coefficient for non-stationarity, numerical regional and large-scale models are thought to underestimate smaller-scale non-stationary motions because of inadequate spatial resolution in the model, damping of such motions by implicit and explicit horizontal diffusion, and possible failure to capture the generation mechanisms.

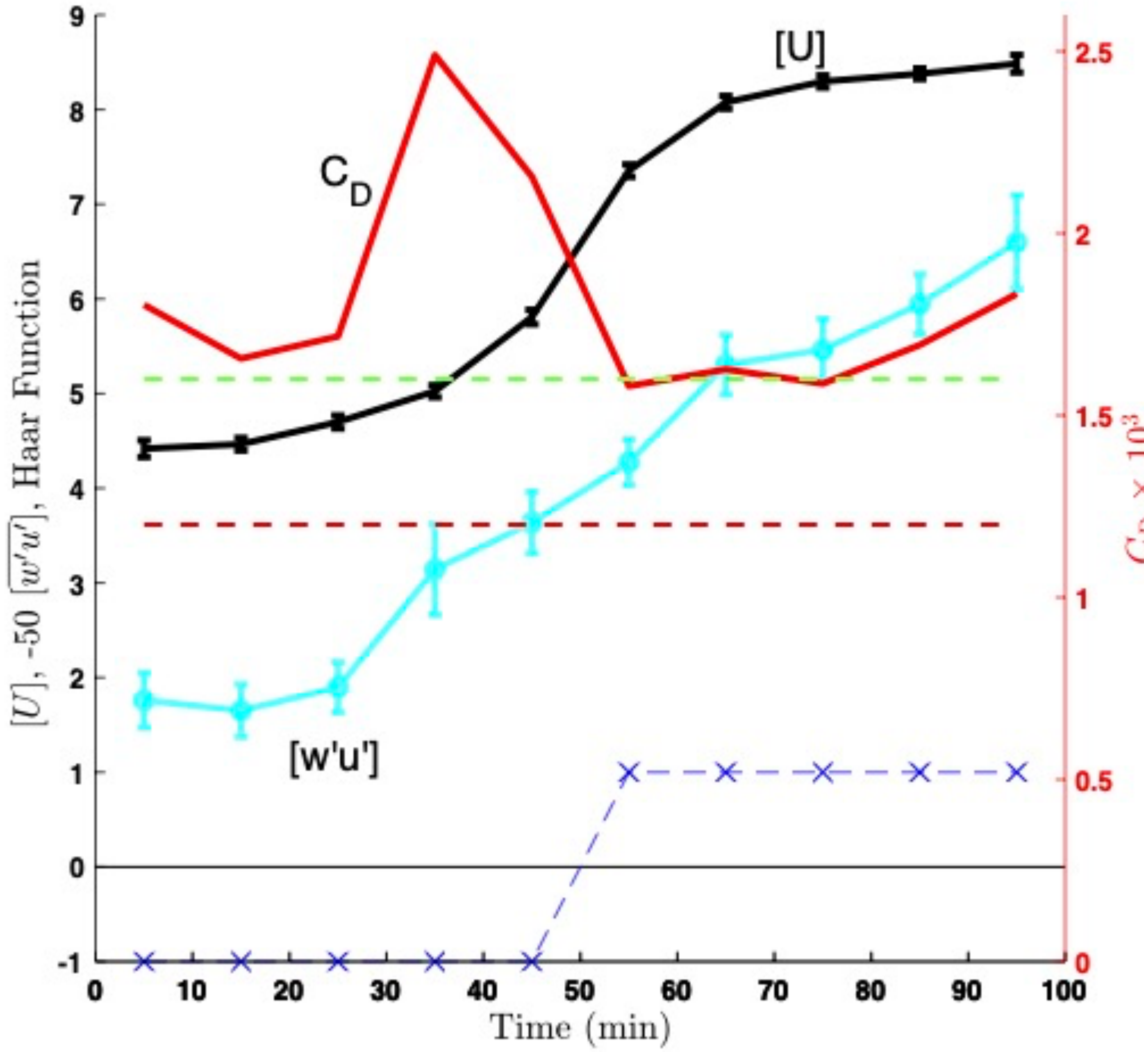

Fig. 1. *Composited structure for the 100 largest increases of the wind speed, U. Shown are U (black), the momentum flux (cyan), and the drag coefficient (red, right axis). The green dashed line is the drag coefficient based on all of the data regardless of acceleration. The red dashed line is the drag coefficient based on averages over all of the data within the wind-speed range of the composited structure. The purple dashed line shows the Haar (step) function used to compute the change of wind speed.*

3. Near-Surface Stress Divergence

Mahrt et al., (2021) analyzed eddy-covariance measurements from two observational levels to investigate the vertical divergence of the stress. For the current data set, the relative stress divergence tends to increase with increasing stability and decrease with increasing instability, probably because the boundary-layer depths are generally smaller for stable conditions. However, no explicit observations of the boundary-layer depth were available. Because of the substantial stress divergence, the magnitude of the surface stress appears to be significantly underestimated by flux observations at standard levels such as 10 m. That is, the calibration of the bulk formula with existing observations is expected, on average, to underestimate the surface stress.

For southerly flow (Fig2a, black, longest fetch), results are summarized in terms of an informal representation of the relative stress divergence in terms of the stability, which provides a basis for model sensitivity studies. Any corrections for the surface stress must be applied with caution because estimating the vertical divergence of the stress is more vulnerable to errors than estimating the stress itself. The averaged relative stress divergence tends to be smaller for short-fetch wind directions because of cases of momentum flux convergence within the average. The magnitude of the stress divergence tends to decrease with increasing wave age, although the generality of this result is not known.

Progress on the influence of wave state on the surface fluxes did not completely meet expectations partly because of the complexity of wave state in inland seas and coastal zones. In addition, the team member who is the expert on wave state became overwhelmed by other issues and her contribution was somewhat reduced from the original plan.

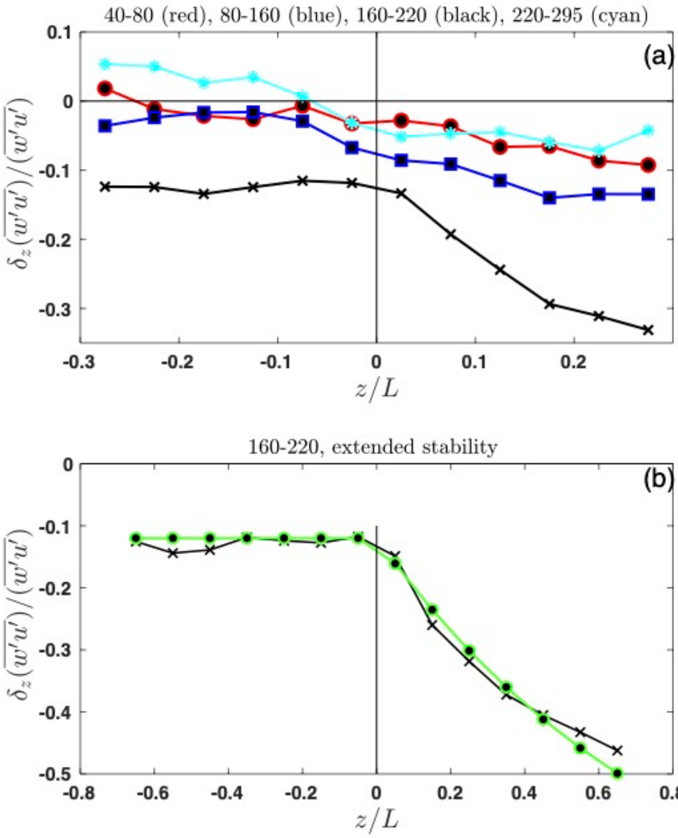

Fig. 2. *The relative stress divergence as a function of z/L for different wind-direction sectors. The wind direction intervals are north-easterly flow of about 200 km fetch (red circles), south-easterly flow of about 200 km fetch, southerly flow (300 -400 km fetch , black X's), and westerly flow (short fetch as small as 4 km, cyan *). b) The relative stress divergence for southerly flow for an extended stability range (black X's). Also shown is an informal fit to the stability (green circles)*

4. The behavior of C_H as a function of stability and fetch

In contrast to typical fair weather boundary layers over land, the air-sea temperature difference (stratification) over the sea is often maintained by advection of temperature, even with high wind speeds and associated mixing. Over land with high wind speeds, significant air-sea temperature differences are typically eliminated by the mixing.

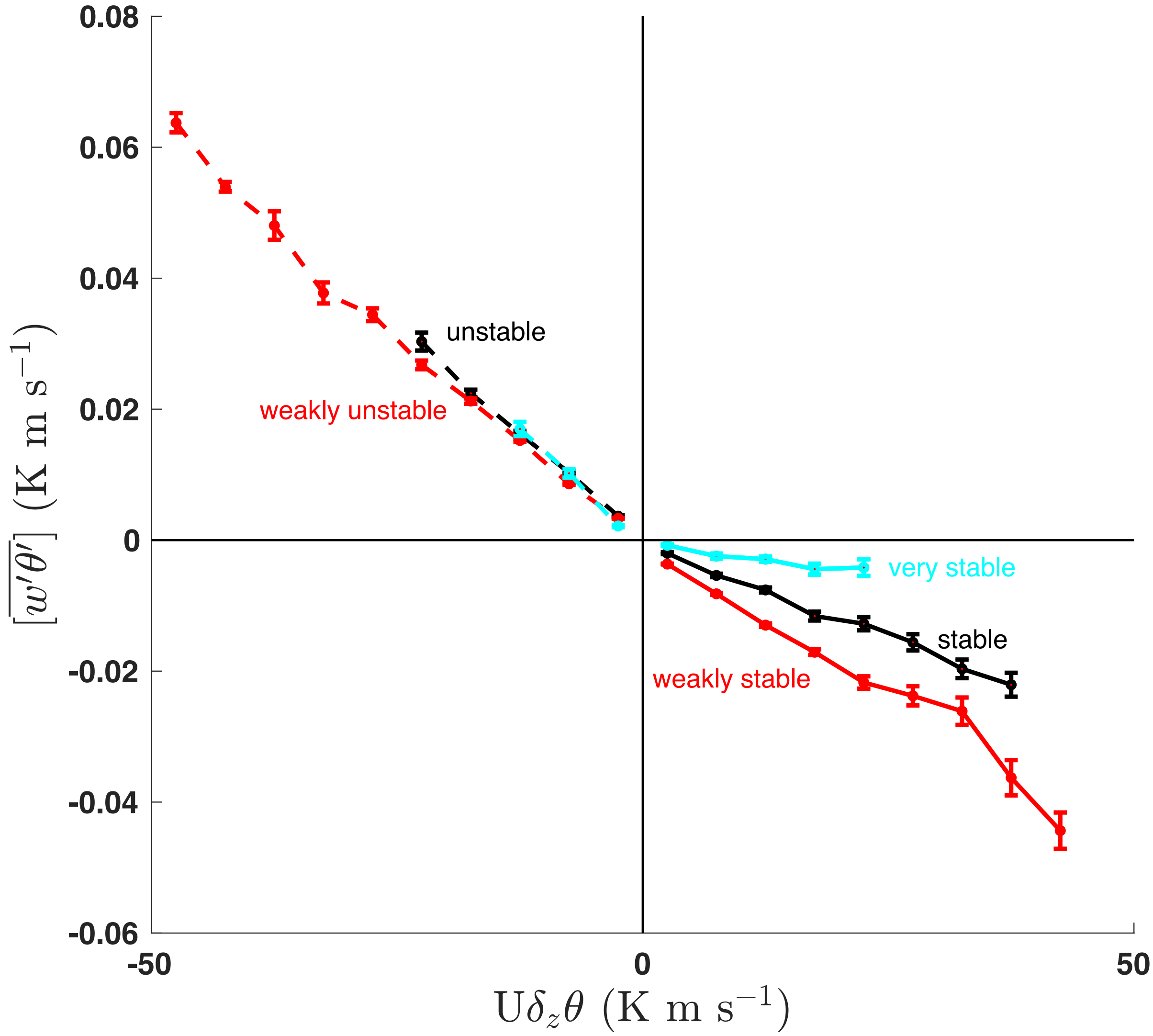

Fig. 3. The heat flux at 10 m related to the forcing by the wind speed and stratification (air-sea temperature difference) for southerly flow for weakly unstable (-z/L <0.2, red dashed), unstable (-z/L >0.2, black dashed), very unstable (-z/L >1, cyan dashed), very stable (z/L >1, cyan solid), stable (z/L >0.2, black solid), and weakly stable (z/L <0.2, red solid). C_H is proportional to the slope of the dependence of the heat flux on the forcing by the wind speed and stratification for southerly flow for weakly unstable (-z/L <0.2, red dashed) and unstable (-z/L >0.2, black dashed).

The sea-surface heat flux was found to be a strong function of the forcing by the wind speed and stratification (Fig. 3), as assumed in the bulk formula, but C_H revealed some unexpected tendencies. For unstable stratification, the upward heat flux could be roughly approximated by a constant C_H for this data, corresponding to constant slope for the dependence of the heat flux on the forcing by the wind speed and stratification, particularly for the long-fetch southerly wind. C_H for stable stratification decreases significantly with increasing stability z/L for all of the wind direction sectors. For large forcing by the the wind speed and stratification, the dependence of the downward heat flux on the stratification is less organized and large values of stratification are maintained for large wind speed, presumably by warm air advection.

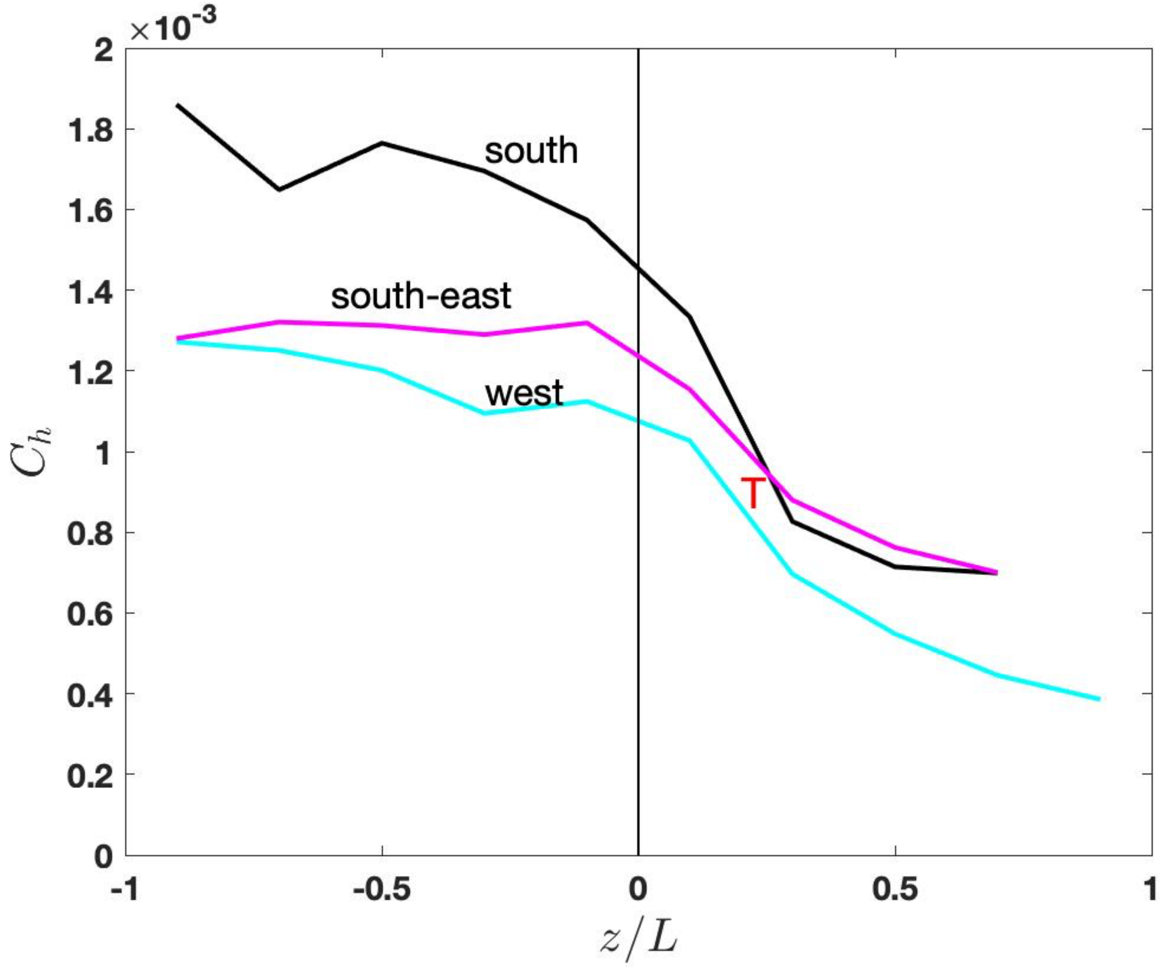

Fig. 4. *The dependence of C_H on z/L for the long-fetch southerly flow (black), the short-fetch westerly flow (cyan) and relatively long fetch south-easterly flow (magenta). The red T indicates a transition (steepest slope) at z/L = 0.2.*

Based on bin-averaged values (Fig. 4), C_H decreases most rapidly with increasing z/L as z/L increases beyond about 0.2, which can be envisioned as the transition of C_H between weakly stable conditions and stable conditions. The transition across neutral stability (z/L = 0) is smaller. C_H was generally smaller for short fetch conditions probably due partly to suppression of large eddies by thin internal boundary layers. The 10-m fluxes underestimate the surface heat flux by 15-30%, being greatest for short-fetch unstable flow and smallest for long-fetch unstable flow. We did not apply these corrections for our default analysis, but the corrections provide an estimate of the potential underestimation of C_H and can be applied *a posteriori*.

5. Impact/Applications

The current report identifies a number of important issues with parameterization of the fluxes in the coastal zone. Our work has suggested specific potential improvements of the flux formulation. While corrections are offered for potential use, their generality is not known. However, potential corrections identified in the above studies can be used for sensitivity studies to assess model uncertainties. For example, relationships have been provided for augmenting the estimated surface flux based on the expected flux divergence between the observational level and the surface. The corrections may be adopted or used as an uncertainty measure. At the same time, more sophisticated formulations of fluxes may not be justified, or may not even improve upon simpler formulations.

Our studies also suggested needed changes in observational strategy which are unfortunately expensive. Estimation of surface fluxes can be improved by including more levels for use in extrapolating fluxes downward to the surface. A sacrificial flux package can be deployed closer to the sea surface, but at a level expected to make it through the summer season.

The expanding Baltic data set could be investigated in more detail. For a subset of variables, the Baltic data set can potentially be extended backward in time to the late 1990's.

6. PUBLICATIONS

Mahrt, L., Erik Nilsson, Anna Rutgersson and Heidi Pettersson: 2020: Sea-surface stress driven by small-scale non-stationary winds. Bound-Layer Meteorol., 47, 689–699. [published, refereed]

Mahrt, L., Erik Nilsson, Anna Rutgersson and Heidi Pettersson: 2021: Vertical divergence of the atmospheric momentum flux near the sea surface at a coastal site. J. Phys. Ocean., 51, 3529-3537 [published, refereed]

Mahrt, L., Erik Nilsson and Anna Rutgersson: 2022: The sea-surface heat flux at a coastal site. J. Phys. Ocean. [submitted]

There was nothing to report under honors/awards, technology transfer, and students.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
04-08-2022	Final Report	01/06/2019 – 31/05/2022

4. TITLE AND SUBTITLE
Inclusion of non-stationarity of the wind and wave fields in the bulk formula for surface fluxes: A new direction

5a. CONTRACT NUMBER
N00014-19-1-2469

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Larry Mahrt

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER
NWRA-22-R207

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Contracting Officer
Office of Naval Research
875 N. Randolph Street Suite 1425
Arlington VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Non-stationarity of the wind field disrupts the equilibrium between the wind, stress, and wave fields. We examined the effect of non-stationarity of the wind field on the stress by analyzing six years of turbulent flux data from the Oestergarnsholm tower in the Baltic coastal zone. On average, the impact of the non-stationarity on the stress and drag coefficient becomes important for wind speeds less than about 6 m/s. The drag coefficient is augmented during the initial stages of acceleration and during the later stages of deceleration.
The underestimation of the sea-surface stress due to the stress divergence between the surface and the 10-m level was investigated. The magnitude of the stress divergence increases modestly with decreasing wave age, increases with increasing stability, and decreases with increasing instability, due partly to the impact of stability on the boundary-layer depth.
We also analyzed heat flux measurements at two levels along with profiles of air temperature, and multiple measurements of the water temperature. We examined simple relationships of the heat flux to the wind speed and stratification and the potential influences of fetch and temperature advection. For a given wind direction sector, the transfer coefficient varies only slowly with increasing instability, but decreases significantly with increasing stability.

15. SUBJECT TERMS
Coastal zone boundary layers, fetch/wind direction dependent, near-surface flux divergence, non-stationarity, wave state

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	U	UL	9	**19b. TELEPHONE NUMBER** *(include area code)*