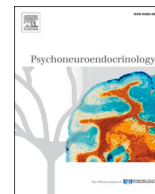Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Allostatic load in the context of disasters

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A B S T R A C T

Environmental disasters, pandemics, and other major traumatic events such as the Covid-19 pandemic or war contribute to psychosocial stress which manifests in a wide range of mental and physical consequences. The increasing frequency and severity of such events suggest that the adverse effects of toxic stress are likely to become more widespread and pervasive in the future. The allostatic load (AL) model has important elements that lend themselves well for identifying adverse health effects of disasters. Here we examine several articulations of AL from the standpoint of using AL to gauge short- and long-term health effects of disasters and to provide predictive capacity that would enable mitigation or prevention of some disaster-related health consequences. We developed a transdisciplinary framework combining indices of psychosocial AL and physiological AL to produce a robust estimate of overall AL in people affected by disasters and other traumatic events. In conclusion, we urge researchers to consider the potential of using AL as a component in a proposed disaster-oriented human health observing system.

1. Introduction

Occurrences of natural and climate-related environmental disasters have risen markedly since the mid-20th century, with devastating costs to both human well-being and economic functioning (Learning and Guha-Sapir, 2013; EMDAT, 2020). In 2020, the United States (US) experienced the highest recorded number of billion-dollar environmental disasters with a total of 22 events, and 20 occurred in 2021 (NOAA, 2022). This continues a 7-year trend of > 10 such occurrences per year following previous records of 16 in 2011 and 2017. Overall, since 1980, the US has experienced 310 weather- or climate-related disasters which caused > $1 B in CPI-adjusted damage costs. Years with > 10 such events include 1998, 2008, 2011–2013, and 2015–2021 (NOAA, 2022).

Both the US and Europe experienced major storms, floods, and wildfires in 2021 (CRED Centre for Research on the Epidemiology of Distasters, 2021; Kaplan and Tran, 2021). Globally, the occurrence of natural disasters, especially associated with climate change, have

increased 1.7-fold in the decade 2000–2019 compared to the previous decade (rising from 4212 to 7348). This increase was associated with 1.23 million deaths, over 4.0 billion people affected – sometimes by more than one disaster event – and estimated economic losses of $US 3 trillion (CRED Centre for Research on the Epidemiology of Distasters, 2020). However, global disaster-associated mortality rates have declined markedly over time, likely in part due to enhanced pre-disaster warnings and preparedness efforts.

Regardless of scale, disasters result in high levels of stress, which is perhaps the most pervasive, pernicious, and persistent adverse health impact of disasters. This distress negatively affects the mental and physical health of individuals and the well-being of entire communities (Sandifer and Walker, 2018; Sandifer et al., 2017; Chandra et al., 2018; Saxbe et al., 2019). The concept of stress permeates our culture at multiple levels and is viewed as consequential to disasters of all varieties. In normal parlance, stress indicates a demanding, sometimes overwhelming, state, accompanied by negative emotions and feelings of inability to cope (McEwen, 2006). However, most disaster preparedness

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and response plans, policies, and programs in the US and elsewhere do not include a central focus on stress and its numerous negative health consequences (Sandifer and Walker, 2018).

Another widespread concern is the lack of sufficient baseline health information against which to compare short- and especially long- term health outcomes and allostatic load following environmental disasters (Goldstein et al., 2011; Colwell and Machlis, 2019; Parker et. al., 2020; Sandifer et al., 2020a). Among others, these include major storms, floods, wildfires, earthquakes, industrial accidents, climate change, along with environmental exposures to large blooms of harmful algae, floodwaters containing infectious organisms and toxic pollutants, mold in previously flooded structures, and the COVID-19 pandemic. Recognition of this critical information gap in the disaster-prone US Gulf of Mexico region led to development of a framework for a comprehensive Community Health Observing System for that region which could also serve as a model for other health observing systems elsewhere (Sandifer et al., 2020a, 2020b).

The Community Health Observing System framework builds on national-level cross-sectional and longitudinal studies in the US. If implemented, this health observing system would add disaster-focused longitudinal cohort studies in the vulnerable coastal areas of the Gulf of Mexico states. Key components of the proposed cohort studies are the collection of biomarkers and other indicators of cumulative stress and health outcomes. While this framework was initiated in response to the massive Deepwater Horizon (DWH) oil spill of 2010, the intent is that the design could be adapted readily to many different types of disasters, including economic catastrophes and pandemics (Sandifer, 2022). A core intent from initiation of the Community Health Observing System framework development was inclusion of allostatic load (AL) as a key metric of disaster-associated health consequences, and we suggest that AL be considered for any health surveillance system implemented for disasters.

2. Characterizing allostatic load

2.1. Value of allostatic load model

The AL model connects cumulative stress with morbidity and mortality (McEwen and Stellar 1993, Seeman et al., 1997; McEwen, 1998, 2000). The value of AL is its use to unravel some of the complex mechanisms by which psychological stress impacts physical health and mental well-being. This utility has been demonstrated many times over the last ~25 years (e.g., see reviews by Juster et al., 2010, 2011; Beckie, 2012; Chandra et al., 2018; Koob and Schulkin, 2019; Guidi et al., 2020). More recently, the AL framework was used to identify effects of stress caused by the COVID-19 pandemic (Peng et al., 2021).

2.2. Assessing allostatic load

Cross-sectional scoring schemes designed to measure multi-system dysregulation as an index of AL have been widely utilized since their initial specification by Seeman et al. (1997) (see reviews by Juster et al., 2010, 2011; Lupien et al., 2015; and others). Typically, AL is assessed via calculation of an index based on a suite of biomarkers. A wide variety of biomarkers has been used for this purpose (Beckie, 2012; Juster et al., 2011; Johnson et al., 2017). Typically, a much smaller subset is selected based primarily on availability in an existing database or ongoing study and/or as perceived or expected utility in identifying negative health outcomes. This approach has led to some controversy regarding the heterogeneity of approaches that deviate from the original concept of AL and relate to inconsistencies in choice and use of biomarkers, determination of biomarker thresholds, and calculation of indices with and without weighting (Beckie, 2012; Gallo et al., 2014; Johnson et al., 2017). Gallo et al. (2014) and Epel et al. (2018) highlighted the lack of a clearly defined and widely accepted "gold standard" for determining AL and standardizing it for comparison across settings and studies.

2.3. Alternative operationalizations of allostatic load

Despite the intuitive nature of cumulative physiological dysregulation over time as a central component of AL, it has rarely been operationalized beyond the count-based approach first developed by Seeman et al. (1997). A notable exception has been the work of Yashin and colleagues which has not been adopted widely (Yashin et al., 2012; Arbeev et al., 2016). In addition, and while not referred to as AL, the considerable literature on frailty indices and their dynamics in elderly populations (Rockwood and Mitnitski, 2007; Farrell et al., 2016; Taneja et al., 2016) may be interpretable as an approach to operationalization of AL beyond strict use of biomarkers. Extension of the frailty literature to younger ages is an important research topic that could enhance the AL discussion and time-course of physiological dysregulations.

Epel et al. (2018) recommend adoption of a stress effects model that "incorporates epidemiological, affective, and psychophysiological perspectives." They propose a comprehensive life course model that includes contextual factors (e.g., genetics; development; environmental, cultural, and social factors; past stress exposures and illness; current and cumulative stress exposures) and protective factors (e.g., supportive family, social, psychological, and behavioral characteristics; habitual processes of pessimism or optimism; and psychological and physiological processes and responses) (Fig. 1). An accompanying stress typology encompasses stressor exposure characteristics, such as timescale (e.g., acute, daily hassles, major life events, chronic); life period of occurrence (in utero, childhood, adulthood); when, where, duration, and target of event (individual, family, community); how effects are assessed; and psychological, behavioral, and physiological responses and measurements. Although Epel et al. (2018) do not present a quantitative formulation of their model, much if not all the information they recommend be considered could be included in AL assessments as described later in this paper.

2.4. Incorporating psychosocial measures of allostatic load

While most of the extant AL reports are based on physiological biomarkers, a particularly salient point is the need to better integrate psychosocial measures with physiological indicators of stress, and with consideration of individual, community, and environmental factors, such as those listed by Epel et al. (2018) as co-variants, moderators, and/or mediators. Specific tools developed to screen for psychosocial AL are the Psychosocial Index presented by Piolanti et al. (2016) and the Diagnostic Criteria for Psychosomatic Research offered by Fava et al. (2019) and Guidi et al. (2020). The Psychosocial Index is based on self-ranked responses to a 55-element questionnaire that can be applied in a clinical situation to assess psychosocial AL. While possible to use in a disaster setting, it may be somewhat difficult to incorporate with collection of biophysical data due to its length. The Diagnostic Criteria for Psychosomatic Research is a shorter and more targeted index that is based on the Psychosocial Index (Fava et al., 2019) and that focuses specifically on a causative stressor event(s), e.g., an environmental disaster or other definable trauma. The psychosocial AL index derived from the Diagnostic Criteria for Psychosomatic Research is determined by responses to a two-part questionnaire, with Criterion A focusing on precipitating events and traumas (the primary recent stressor or stressors of note) and Criteria B targeting psychosocial impacts on individuals and their lives. Answers affirming significant effects related to both sets of Criteria would result in a diagnosis of psychosocial AL (Tables 1 and 2).

3. Predisposing, mediating, and compounding factors

The long history of socioeconomic and racial disparities in health care, along with globally-impactful, slow-moving disasters such as climate change and now the COVID-19 pandemic, as well as more acute and periodic catastrophic events such as hurricanes, floods, wildfires,
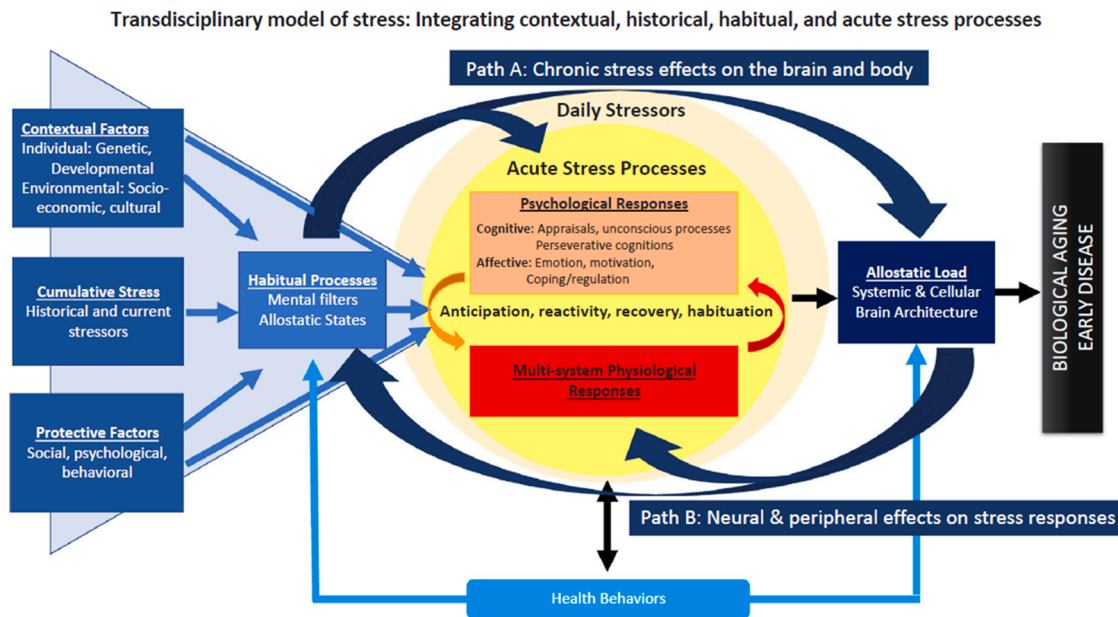
Transdisciplinary model of stress: Integrating contextual, historical, habitual, and acute stress processes

Fig. 1. Transdisciplinary model that describes "stress" as a set of interactive and emergent processes. The figure illustrates that stressors are experienced within the context of a person's life, represented by the contextual factors in the blue triangle. These contextual factors include individual-level characteristics such as personality and demographic factors, the environment in which one lives, current and past stressor exposures, and protective factors. Collectively, all factors combine to determine the baseline allostatic state of physiological regulation, and the lens through which stressors are perceived and assigned meaning. Contextual factors and habitual processes together influence psychological and physiological responses to acute and daily stressors. These responses, if dysregulated, are thought to lead to allostatic load and ultimately biological aging and early disease (from Epel et al., 2018, used with permission).

and others, will continue to lead to negative health outcomes in society at large and especially among marginalized groups. High AL is regularly correlated with all-cause mortality (Seeman et al., 2001; Gruenewald et al., 2006; Borrell et al., 2010; Howard and Sparks, 2016; Robertson et al., 2017; Castagne et al., 2018), individual disorders such as cardiovascular disease (Cohen et al., 2007; Cadar et al., 2018), and in relation to socioeconomic position (Johnson et al., 2017). It is now also associated with global climate change (Crews et al., 2019). Higher AL scores are often encountered among minorities and in low-wealth communities (Johnson et al., 2017; Borrell et al., 2020). These communities frequently bear the brunt of catastrophic events including the COVID-19 pandemic (Lopez et al., 2021) and climate change (USGCRP, 2018; Dietz et al., 2020). People in such communities who already experience higher AL levels "can reasonably be expected to have an impaired immune response to novel pathogens such as SARS-CoV-2″ (Dasco et al., 2020). Increased exposures to harmful algal blooms and their toxins, oil spills, and other injurious substances and circumstances can be expected to add to individuals' stress levels and hence to AL, particularly in coastal communities (Sandifer, 2022). Substantial evidence shows that a variety of influencing factors may be associated with AL (see in particular, Epel et al., 2018 and Table 3), but much remains to be done to understand the interactions between and among these factors, and how they may exacerbate or mitigate AL and its consequent mental and physical disorders.

4. Allostatic load in the context of disasters, traumas, and pandemics

4.1. Using AL for disaster-health impact studies

While a fully developed theoretical foundation remains to be formulated for AL, we know enough to use AL to predict the likelihood of negative stress-associated health outcomes and begin to assess effects of disasters on the trajectory of AL and its health implications for individuals, groups, and communities. Here, we take a pragmatic approach, one focused on potentially useful diagnostic/predictive

methods for harmful stress responses in the context of disasters and other traumatic events, including the present COVID-19 pandemic and its social and economic disrupting effects.

Notwithstanding the widely recognized association of stress with disasters, relatively little work has been done to incorporate objective measures of physiological stress such as AL in disaster-related health studies. McEwen (2005) noted "[I]f the additional load of unpredictable events in the environment (e.g., **storms, natural disasters**), **disease outbreaks** [emphasis added], disturbances caused by humans and antagonistic social interactions is superimposed, then AL can increase dramatically to become allostatic overload. Allostatic overload serves no useful purpose and predisposes the individual to disease." McEwen and Tucker (2011) suggested that AL could be useful in evaluating risks associated with exposure to toxic chemicals, particularly chronic exposure via contaminated sites, and termed such situations technological disasters.

There are other interjections of AL into disaster discussions, but usually these follow a particular event and are related to a specific health outcome such as heart attacks (Kario et al., 2003). Recent recommendations include incorporating AL in evaluating disaster-related human health effects associated with degradation of ecosystem services and making stress and AL a key focus of future disaster-related health research (Sandifer and Walker, 2018). The COVID-19 pandemic provides a heretofore unprecedented opportunity to assess the impact of similar stressful experiences on populations all over the world, which are operating under diverse political, social, and economic conditions. Stress impacts are perhaps most apparent in the psychosocial effects of the pandemic. Some researchers are now forecasting widespread mental and behavioral disorders associated with the COVID-19 pandemic and its stress, with estimates as high as 10% of the global population being affected (Galea et al., 2020; Soloveva et al., 2020; Breslau et al., 2021).

4.2. Harnessing allostatic load for disaster response

Although some AL studies have involved longitudinal cohorts, many have not. This is surprising in light of the numerous times that the need

Table 1

Diagnostic interview for determination of psychosocial allostatic load (PsyAL) (modified slightly from Table 2 in Fava et al., 2019) with minor wording changes and explicit inclusion of disasters).

Psychosocial Allostatic Load Criteria	Questions	Response	
Criterion A. The presence of at least 1 current identifiable source of distress in the form of recent life events and/or chronic stress. Considering the full nature and circumstances of the stressor(s), do you judge it/them to have taxed or exceeded your ability to cope?	**A.1** In the last 12 months ■ Did you experience a major environmental or other disaster or traumatic event? ■ Did a family member or close friend die? ■ Did you separate or divorce from your partner? ■ Did you change or lose job? ■ Did you move? ■ Did you have severe economic difficulties? ■ Did you have legal problems? ■ Did you start a new relationship? ■ Did you feel under pressure at work? ■ Did you have problems with co-workers? ■ Have you been a victim of bullying, stalking, severe interpersonal pressure, or domestic violence? ■ Did you have problems with your spouse/partner or other family members? ■ Did you feel tension at home? ■ Has at least 1 family member been seriously ill? ■ Other A.2. Have you felt that life is asking too much of you?	**Yes**	**No**
Criterion B. The stressor is associated with 1 or more of the following features, which have occurred within 6 months of onset of the stressor: at least 2 of the following symptoms: difficulty falling asleep, restless sleep, early morning awakening, lack of energy, dizziness, generalized anxiety, irritability, sadness, demoralization	**B.1.** Within 6 months of onset of (NAME OF THE STRESSOR) ■ Did you take a long time to fall asleep? ■ Did you wake up many times during the night? ■ Did you often wake up too early and could not get back to sleep? ■ Did you feel tired, without energy? ■ Did you feel a sense of instability, dizziness? ■ Did you feel nervous or anxious? ■ Did you feel irritable? ■ Did you feel sad or depressed? ■ Did you feel demoralized?		
Significant impairment in social/occupational functioning Significant impairment in environmental mastery (feeling overwhelmed by the demands of everyday life)	**B.2.** Did you have problems or difficulties at work, at home, or in relationships with other people? **B.3.** Did you feel overwhelmed by the demands of everyday life?		

Diagnosis of Psychosocial Allostatic Load (PsyAL): A1 = Yes + A2 = Yes + B1 and/or B2 and/or B3 = Yes = PsyAL.

Table 2

Clinical criteria for allostatic overload (A through B are required) (from Fava et al., 2019).

Criterion A The presence of a current identifiable source of distress in the form of recent life events and/or chronic stress; the stressor is judged to tax or exceed the individual coping skills when its full nature and circumstances are evaluated

Criterion B The stressor is associated with one or more of the following features, which have occurred within 6 months after the onset of the stressor:
1. At least two of the following symptoms: difficulty falling asleep, restless sleep, early morning awakening, lack of energy, dizziness, generalized anxiety, irritability, sadness, demoralization
2. Significant impairment in social or occupational functioning
3. Significant impairment in environmental mastery (feeling overwhelmed by demands of everyday life)

Table 3

A partial list of preexisting influencing factors and challenges that may affect the development and manifestations of psychosocial and physiological allostatic load (informed by Beckie, 2012; Johnson et al., 2017; Sandifer et al., 2020b; Epel et al., 2018; Christensen et al., 2019; Fava et al., 2019; Milad and Bogg, 2020; White et al., 2020; Obeng-Gyasi et al., 2021). This list is intended to be illustrative and is not exhaustive.

Behavioral Factors	Genetics
Diet	Family disease history
Smoking	Known genetic issues (e.g., BRCA gene for breast cancer)
Alcohol/drug use	**Personality Traits**
Physical exercise	Type A vs Type B personality
Sleep Habits	Agreeableness
Biographical/Demographic Factors	Conscientiousness
Age	Extraversion
Sex/Gender/Preference	Neuroticism
Marital/partner status	Openness
Children	**Psychosocial Factors**
Socioeconomic & Educational status (SEES)	Anxiety, including illness anxiety
Employment status	Depression
Occupation	Optimism
Work environment	Pessimism
Income	Anger/hostility
Childhood Experiences	Coping
Adverse childhood experiences (ACES)	Self-mastery
Economic, social, or other deprivation	Sense of control
Clinical Factors	Resilience
Chronic disease (e.g., CVD, diabetes, cancer)	Loneliness/isolation
Treatment	Feelings of security/insecurity
Medications	Quality of life
Medical Procedures	
Environmental Factors	**Stress/Trauma History**
Neighborhood characteristics (including "green" and "blue" spaces)	Previous highly stressful events, times of occurrence, duration, time course
Social and familial support	Current major stressors
Cultural and/or religious aspects	Chronic stress (e.g., from care giving, job)
Health care	
Housing status	
Exposure to toxic or disease-causing substances or organisms	

for dedicated prospective longitudinal studies to advance AL has been identified (Seeman et al., 2001; Piazza et al., 2010; Beckie, 2012; Juster et al., 2011; Buckwalter et al., 2015; Fernandez et al., 2015; Gallo et al., 2014; Howard and Sparks, 2016; Mauss et al., 2016; Solis, . et al., 2016; Castagne et al., 2018; Epel et al., 2018; Picard and McEwen, 2018a, 2018b). Also, most AL research to date does not include psychosocial data in calculation of an AL index or as a complement to physiological AL formulations.

The potential to operationalize AL for use in disaster-health studies was discussed extensively at an expert workshop convened for the express purpose of evaluating options for operationalizing AL (see Sandifer et al., 2020b and acknowledgments for details). Some of the discussion

revolved around the possibility of developing a short form of AL or "AL light" for use in disaster contexts. Since a comprehensive measure of multiple neuroendocrine, immune/inflammatory, metabolic, and cardiovascular parameters is costly, a simplified "AL light" could lend itself well to field research. Ideas for an abbreviated formula for AL have been circulating for years, with examples provided by Kanel et al. (2003), Evans et al. (2007), Gersten (2008), Evans and Schamberg (2009), and Seeman (AL Expert Workshop presentation, Feb. 2019), among others.

Researchers have used various numbers of biomarkers based on convenience or other considerations. For example, while Mauss et al. (2015) initially used a total of 15 biomarkers, Mauss et al. (2016) found that a streamlined AL index based on just five – diastolic blood pressure, waist circumference, glycosylated hemoglobin, low density lipoprotein, and heart rate variability – worked well to demonstrate association between high levels of industrial work-related stress and AL in male workers. They concluded that "[a] short form index seems to be a promising approach for occupational health practitioners," and suggested further validation in longitudinal studies and development of a standardized suite of indicators. While this approach is interesting, there is no agreement on what parameters to definitely include when calculating AL. At a minimum, a determination of which biomarkers should be included in an abbreviated AL, particularly a formulation that could be used in multiple contexts is needed. Without an expert consensus, it is doubtful that one can be developed easily. In particular, a principal concern is the failure to include neuroendocrine mediators of AL in all abbreviated formulations or the inclusion of immune mediators as well as the downstream secondary outcomes reflected in metabolic and cardiovascular biomarkers.

4.3. What is needed to apply AL in disaster contexts?

In order to be of broad use in high-stress contexts such as disasters, a practical construct of AL needs to: (1) be as comprehensive as possible, including assessment of predisposing or influencing factors and psychosocial as well as physiological indicators that capture both the original causative experiences and resulting psychological and physiological responses; (2) have high fidelity in correspondence to the original concept as defined by McEwen, Seeman and others and include primary mediators; (3) incorporate biomarkers from multiple systems (neuroendocrine, immune/inflammatory, cardiovascular, respiratory, metabolic, anthropomorphic) to provide a robust index; (4) incorporate application and tracking within long-term longitudinal cohorts; and (5) have capacity to integrate new metrics as knowledge and technology advance.

5. Potential way forward to apply allostatic load in disaster contexts

5.1. Proposal to include both psychological and physical allostatic load

We propose combining simultaneous calculation of indices for psychosocial AL and physiological AL where requisite data are available. While we do not think it would be appropriate to attempt to calculate a single index score that would include both forms of AL at present, having both scores for the same people and following their evolution over time among participants within cohorts will provide robust indications of cumulative health effects and interactions of stress from psychosocial and physiological standpoints.

5.2. Using the community health observing system to test the concept

The Community Health Observing System recently proposed by Sandifer et al. (2020a, 2020b) for the disaster-prone Gulf of Mexico region in the US could provide an excellent platform from which to test this concept (Suppl. Fig. 1). While the initial motivation for development of this observing system framework was recurrent environmental

disasters in the Gulf of Mexico region, the basic health observing system plan could be adapted for use in many other geographic areas and other kinds of traumatic events including the COVID-19 pandemic. The framework relies on existing national (and mostly cross-sectional) health surveys conducted by the Centers for Disease Control and Prevention (CDC) and the National Institute of Health's (NIH) new All of Us longitudinal study for comparative information at the national scale as well as community condition indicators such as the American Community Survey. However, the central and unique features of the proposed system are three new, nested longitudinal cohort studies: a Large Cohort that would provide a representative sampling of populations in the study region, a Small Cohort that would encompass a subset of the Large Cohort the members of which agree to provide more clinical data as well as biological specimens, and Disaster-Specific Cohorts that would be established rapidly following a disaster and built as much as possible upon the Large and Small Cohorts. (Suppl. Fig. 1).

Disaster-specific cohorts could be defined based on the geographic footprint of a specific disaster (e.g., hurricane), the type of event (e.g., economic disruption, pandemic), or even a particularly vulnerable community or population. Health data collected in the Large Cohort would comprise participant personally provided information obtained using questionnaires similar to those employed in the national cross-sectional studies along with a considerable amount of clinically-derived data. Much more clinical data including biological specimens would be collected in the Small and Disaster-Specific Cohorts (Table 4), and supplementary data would be gathered from a variety of additional means including syndromic surveillance, electronic health records, wearable health monitors, remote sensing, social media, telemedicine assessments, and others to name a few examples (Suppl. Fig. 1). As noted in the Discussion, trained teams, consent and data collection protocols, supplies and materials, and institutional review board (IRB) approvals could be prepared and put in place on a region-by-region basis prior to disaster events. Like other disaster response plans, these should be updated regularly.

The Diagnostic Criteria for Psychosomatic Research or longer form Psychosocial Index could be included in the participant questionnaire, which already includes several psychosocial indicators as well as information on numerous potentially predisposing, mediating and/or moderating factors (Table 3). Factor analytic approaches to reduce multiple variables into key components or the use of indices that combine multiple variables into similar constructions could be useful in this endeavor. All health observing system Cohort participants would complete the participant questionnaire thereby providing the data to calculate the psychosocial AL index for all. In addition, physiological AL could be assessed for participants in the Small and Disaster-Specific Cohorts, based on the wide range of biomarkers expected to be collected (Suppl. Table 1). Having both psychosocial AL and physiological AL calculations for individuals would provide stronger predictive tools for potential negative health outcomes and allow assessment of interactions between psychosocial and physiological factors and the pre-existing conditions that affect both (Fig. 2).

While establishing a standard set of biomarkers should improve reproducibility and comparability of results across studies (Johnson et al., 2017), suggesting such is beyond the scope of this paper. However, at minimum, we recommend that researchers consider the original 10 indicators used by Seeman et al. (1997) (neuroendocrine system/HPA axis: cortisol, dehydroepiandrosterone sulfate, epinephrine, and norepinephrine; cardiovascular system: systolic and diastolic blood pressure; metabolic system: total cholesterol, high density lipoprotein; glycosylated hemoglobin; anthropomorphic: waist-hip ratio) and attempt to balance neuroendocrine, immune, metabolic, and cardiovascular parameters. Many physiological biomarkers previously used or recommended for use in calculating physiological AL are listed by Juster et al. (2010, 2011) and Sandifer et al. (2020a, 2020b) and others (Suppl. Table 1). Note that while some research has focused on the primary mediators of AL (Gersten, 2008), it may not be sufficient to focus on

Table 4

Types of data proposed for collection in the Gulf of Mexico Community Health Observing System cohort studies. All but personally provided information will be obtained in clinical settings. Modified slightly from Sandifer et al. (2020a, 2020b).

Personally Provided Information From Questionnaires	Physical Health Measures
Demographic information, including ethnicity, sex/gender identity, marital/partner status, children	Systolic & diastolic BP
Socio-economic information, including ability to deal with minor financial emergencies	Pulse (heart) rate
General health status	Height & Weight
Personal health history, including chronic and major diseases	Waist-hip ratio
Family health history, including chronic and major diseases	Body mass index (BMI)
Life history and behavioral factors, including alcohol, tobacco, and illicit drug use, nutrition, exercise, sleep	Lung function (FEV1/FEVC)
Health care access and services utilization	Cardiovascular fitness
Prescribed medications	Gum health
Previous disaster/trauma experiences including in childhood	Balance
Residence and adequacy of housing	Ambulatory fitness (ability to rise, stand, walk)
Known or suspected exposure to toxic or infectious substances or organisms	**Biospecimens**
Social, religious, tribal, community attachments and memberships	Blood
Marginalization and discrimination (political, racism, ethnic, ageism, economic)	Plasma
Feeling of security or insecurity in home and neighborhood	Serum
Level of trust in government/societal structures	Saliva
Mental health measures	Urine
Anxiety: GAD-7	Hair
Depression: PHQ-8 or 9	DNA, mt DNA, telomere length (buccal swab)
PTSD/PTSS: PTSD Civilian	Nails (finger and toe)
Resilience: CD-RISC-10 (Connor-Davidson Scale)	Stool
	Breath
Alcohol abuse: AUDIT-C	Umbilical cord blood (when available)
Religiosity: RQ-12	
General self-efficacy scale (GSES)	
Social capital (adapted from loneliness scale (ULS-8)	
Sense of control scale	
Cognitive function (IQ or other)	

these without consideration of secondary outcomes (Loucks et al., 2008). With the rapid advance of measurement technologies (e.g., multiplex, mass spectrometry), ambulatory assessments of many biomarkers (e.g., diastolic and systolic blood pressure, heart rate variability, glucose, cortisol, and others), as well as environmental exposures will become routine in the future. These and other indicators could be added to ongoing cohort studies as measurement technologies mature.

6. Discussion

McEwen and Stellar (1993) put forth an elegant concept they termed AL to link adverse physical health effects to cumulative psychosocial stress. In the decades since their initial description and its first operationalizations by Seeman et al. (1997), AL has been described in multiple contexts using varying physiological biomarkers and more recently psychological metrics. Although a complete theoretical underpinning for AL has yet to be developed, AL is well established as a composite diagnostic tool for assessing toxic stress in contexts such as disasters. It is this utility we review here and recommend for further application for disaster-associated health impacts in a world increasingly fraught with environmental and other catastrophes.

Despite nearly three decades of AL-related research and many papers on the topic, there is no fundamental understanding of how AL works. AL was originally described in people, which is undoubtedly the most complex organic system in which to try to understand mechanisms of action. AL also has been employed to assess health status and predict disease risk in captive non-human primates, including gorillas (Edes et al., 2018, 2020) and lemurs (Seeley et al., 2021) and may have potential for much broader application in animal husbandry. However, mechanistic underpinnings for AL have yet to be comprehensively described. The lack of new conceptual formulations of AL combined with empirical studies on simpler animal systems is a major bottleneck to further progress. We strongly recommend that younger scientists with fresh ideas and the latest technologies attack this problem in a comprehensive fashion, starting with new hypotheses and working with non-primate animal models, perhaps beginning with something like C. elegans and then moving up the taxonomic tree to higher animals such as small fish and mice.

Harmful levels of acute, chronic, and cumulative stress, and their psychological, physiological, and social impacts, are hallmarks of disaster events and other traumas. However, there is much yet to be learned about AL and the time course of physiological dysregulations in different contexts. While prospective longitudinal cohort studies provide the best mechanism for identifying AL and beginning to unravel how it works mechanistically, most existing cohort studies were not established with assessment of stress impacts on health in mind. As a result, it has been difficult to obtain sufficient biomarkers and psychosocial indicators post-hoc in such studies. This has contributed to the frequent differences in biomarker use and difficulties in comparing results across studies identified by numerous researchers.

Here, we offer the recently proposed Gulf of Mexico Community Health Observing System to comprehensively address and assess AL. If implemented, a broad range of AL metrics as noted above would be built into the system from the beginning. The health observing system would also include a plan for incorporation of other metrics as they become available or are identified as having particular salience. A pilot human health observing system project, perhaps located in the central Gulf of Mexico region, could be used to demonstrate the usefulness of the approach and fine-tune its design for broader implementation (Sandifer et al., 2021). The ultimate goal will be to build a linked network of regional health observing systems across the US (Sandifer 2022).

Regional health observing systems could include a quick response or "strike team" capacity "to rapidly identify participants, collect data, and provide treatment or referrals immediately following a disaster" (Sandifer et al., 2020b). Building such a capability would require the development of a trained cadre of rapid health responders supported by pre-approved data collection protocols and response plans, stockpiles of equipment and supplies, pre-identification of clinical, laboratory, and analytical capabilities, establishment of IRBs specifically designed and empowered to conduct rapid reviews, integration of the health responders into local and regional emergency response strategies, and the resources to maintain these capacities over time.

While we know of no fully operational and comprehensive health strike teams that could be mobilized rapidly in times of disaster, important progress has been made by the National Institute of Environmental Health Sciences (NIEHS) and its parent agency NIH in its Disaster Response Research (DR2) program that was born out of needs identified following the DWH oil spill (Miller et al., 2016; https://www.niehs.nih.gov/research/programs/disaster/index.cfm). Although the need for rapid IRB approvals apparently remains a concern, the One-Florida Clinical Research Consortium provides an example of a large entity that has established a single IRB to support work of multiple institutions (https://www.ctsi.ufl.edu/ctsa-consortium-projects/oneflorida/, Shenkman et al., 2018). Rapid response capabilities, including a multi-institutional IRB with ability to conduct reviews and make decisions rapidly, could become an integral part of regional health observing systems. Other parts of the world could consider similar

Pre-existing Influencing Factors

Behavioral

Biographica

Childhood

Clinical

Demographic

Environmental

Genetic

Personality

Psychosocial

Stress

Trauma

DCPR (PsyAL) ⟶ Psychological disorders*

Disaster Event(s)

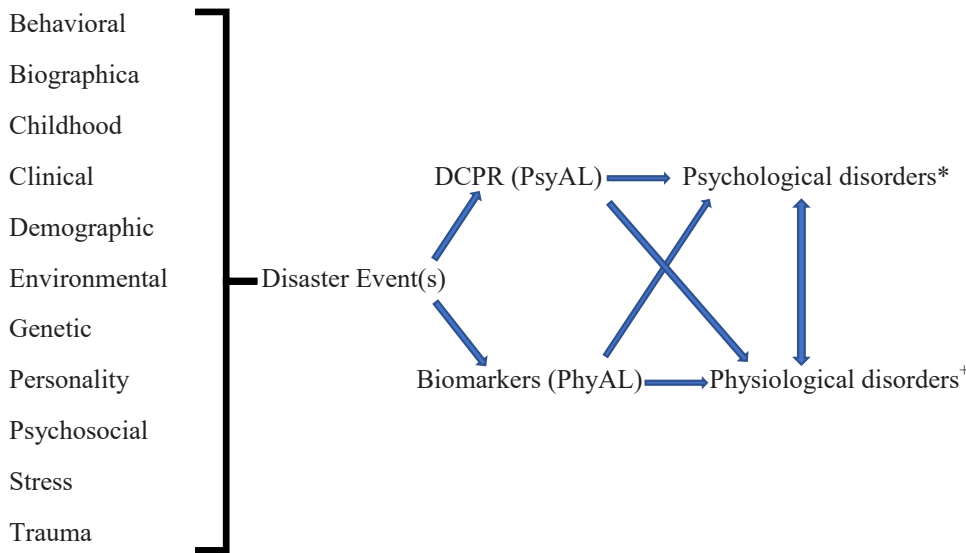Biomarkers (PhyAL) ⟶ Physiological disorders[+]

Fig. 2. Simple graphical representation of inclusion of pre-existing influencing factors in calculations of both psychosocial allostatic load (PsyAL) and physiological AL (PsyAL) and some of their associated health outcomes. Arrows also indicate likely interactions whereby PsyAL may produce or exacerbate physiological as well as psychological disorders and vice versa as well as interactions between the disorders (e. g., impacts of chronic anxiety on cardiovascular diseases). Calculating both PsyAL and PhyAL for the same individuals in long-term cohort studies would allow consideration and assessment of such interactions over the life course and multiple traumatic events. (*Includes but not limited to anxiety, depression, PTSS, eating disorders, substance abuse, interpersonal conflict, difficulty concentrating, malaise, mood issues. [+] Includes but not limited to cardiovascular disease, respiratory and digestive complaints, headaches, and others).

platforms in anticipation of potential disasters.

Regardless of whether a health observing system is implemented in the near term, efforts should be undertaken to establish prospective cohort studies for the specific purpose of assessing, validating, and understanding AL and its utility in predicting and thereby enabling mitigation of unnecessary morbidity and mortality related to stress, whether associated with disaster events, pandemics, climate change, or other factors. Although most reports of AL scores in the literature are based on physiological assessments, including the psychosocial AL questionnaire in one form or another in a health surveillance system, along with physiological AL based on biomarkers, would provide the most comprehensive assessment of AL and its utility in predicting and following disaster-associated health outcomes. Peng et al. (2021) demonstrated the utility of Fava's (2019) clinimetric approach to assess AL associated with the COVID-19 pandemic among medical nonmedical workers, using the 55-item Psychosocial Index. Their study was conducted online in China about 6 months into the pandemic and involved approximately 3600 participants. The investigators reported AL in 15.8% of medical and 17.8% of nonmedical workers with no significant differences in these levels. However, factors associated with AL differed between the groups, with medical workers more stressed by work dissatisfaction and conflicts and nonmedical workers more by loss of jobs and difficult family issues. They also found that "anxiety, depression, somatization, hostility, and abnormal illness behavior were positively associated with allostatic load, while objective support, subjective support, utilization of support, social support, and global well-being were negatively associated." Adding physiological AL metrics would have given a much more nuanced and complete assessment as would following of AL over the long term in longitudinal cohorts.

Peters et al. (2021) note that, while stress is typically considered to cause adverse psychological and physiological problems, some acute stress responses can also have positive effects, including the promotion of effective immune responses to viral diseases. They suggest the use of health questionnaires such as the Short Form Health Survey (SF-12) to help identify those whose pre-exposure psychosocial stress levels or positive quality of life may either increase or reduce their susceptibility to infectious disease. The comprehensive assessments of AL that would be a major component of the type of health observing system proposed here would make possible early identification of people who may need

interventions to reduce their vulnerability.

As is often the case with environmental disasters, individuals and communities already disadvantaged by socioeconomic conditions, racism, health disparities, limited access to health care, low income and wealth, poor quality housing, and disproportionate exposure to pollutants and other environmental stressors are suffering higher impacts from COVID-19 (Lopez et al., 2021; Terrell and James, 2020) and global climate change (Islam and Winkel, 2017; Ebi et al., 2018; EPA, 2021; Romanello et al., 2021). COVID-19 has significantly reduced overall life expectancy in the U.S., with the impact for Black and Hispanic people 2–3 times greater than for others (Woolf et al., 2021). Further, minorities and people with poorer health often tend to be less well represented in health studies than non-minority and healthier individuals (Signorello et al., 2005; Enzenbach et al., 2019), so less is known about their prior and ongoing health issues. Many low-wealth, predominantly minority communities are located in proximity to ongoing or legacy industrial sites, highways, and other operations that produce significant environmental exposures (Solomon et al., 2016). Communities in such areas frequently suffer limited health care access, poor housing, low incomes, lack of green space, exposure to violence, racism, and ongoing health disparities and are often referred to as environmental justice (EJ) communities. Previous studies have reported that black and African American persons frequently had higher AL scores and mortality than others (Duru et al., 2012; Borrell et al., 2020; Geronimus et al., 2006; Howard and Sparks, 2016). Similarly, lower education and income levels are associated with higher AL and biological risk, independent of race/ethnicity or other factors (Seeman et al., 2004, 2008; Beckie, 2012; Borrell et al., 2020). Thus, it is not surprising that populations of EJ and other disadvantaged communities may have increased AL and/or weakened immune responses (Cave et al., 2020; Dasco et al., 2020).

Wakefield and Baxter (2010) used the term "*compounded disadvantage*" to describe the "multiple, overlapping health challenges faced by marginalized communities." This concept takes into account social standing and identity, as influenced by environmental and social injustices that are associated with degraded physical and social environments and poorer health and well-being. Environmental justice and climate justice are linked, and both should focus on local impacts, lived experience, vulnerabilities associated with systemic inequalities, and community voices (Schlosberg and Collins, 2014). These are among the

basic principles of community based participatory research.

Palinkas et al. (2021) described the vital roles that nongovernmental community organizations have played in COVID-19 responses in building, supporting and sustaining resilience in underserved Louisiana communities and their potential for continuing and expanded roles related to climate change impacts. One such organization is the Community Resilience Learning Collaborative and Research Network (C-LEARN) (https://www.c-learn.org) established in 2017 in Southeast Louisiana as a community-academic partnership "to enhance community and individual resilience in communities threatened by climate change and related disasters" (Springgate et al., 2021). Another excellent example is the Lowcountry Alliance for Model Communities (LAMC) and its associated research and analytic arm, the Charleston Community Research to Action Board (https://lamcnc.org/). This is a well-established and accomplished community based organization founded in 2005 that encompasses a group of eight EJ communities in Charleston, South Carolina, with outreach to others. Partnering with such community-based organizations and community leaders requires commitment to a community based participatory research approach that values input and participation equally from community and academic partners. It effectively ensures that community voices are not only heard but incorporated into projects. The community based participatory approach was built into the Community Health Observing System framework from the beginning (Sandifer et al., 2020a). Additionally, the proposed observing system includes disaster-specific cohorts that would be established to follow effects of individual disasters as well as their additive and synergistic impacts for areas or groups that suffer repeated calamities. Such cohorts could be created in environmental justice communities to assess psychosocial and physiological AL periodically over time for people who not only experienced one or more disasters but also significant pre-disaster and ongoing environmental, socioeconomic, and health stress. Regular measurement of AL in individuals from environmental justice and similar communities could provide ongoing individual and community health assessments and data for comparison with people living in more advantaged circumstances, uncover new information about how AL works and how stress causes specific health issues, and help identify where health care and social interventions might be most efficacious in reducing stress-associated disease burden. Building new partnerships involving biomedical and public health researchers, community leaders, and community based organizations could be an effective way to launch and manage longitudinal cohort studies in EJ and other communities.

As designed, the Community Health Observing System would provide long-running (hopefully continuous) cohorts, with data collection set at regular intervals, so that AL could be followed over the life course. This combined approach would open possibilities of (1) reporting both psychosocial and physiological AL indices for a more robust composite index, (2) using the psychosocial data to help explain physiological results obtained from biomarkers, (3) exploring interactions between psychosocial and physiological factors and outcomes, and (4) ensuring inclusion of substantial representation from marginalized communities. Most importantly, the evolution of individual AL scores could be followed over time for individuals and within groups and across multiple disasters/traumas and inter-disaster recovery periods, addressing crucial gaps in the AL literature and in our understanding of cumulative stress impacts.

7. Conclusions

A decade ago, Beckie (2012) described the need we address, stating: "Priorities for future research include conducting prospective longitudinal studies, examining a broad range of antecedent allostatic challenges, and collecting reliable measures of multisystem dysregulation explicitly designed to assess AL, at multiple time points, in large population-representative samples. Longitudinal data will facilitate the test of selection effects and allow for estimates of within-cohort age

trajectories that represent true developmental changes with age, thus distinguishing aging and cohort effects (Yang and Kozloski, 2011)."

Additional priorities now include the pressing need to address not only health effects of environmental disasters but also long-term mental and physical health impacts of the COVID-19 pandemic and acute and more slowly developing consequences of global climate and environmental change. These will require a much more comprehensive and equitable approach to health management, recognition of the pervasive influences of stress on health and well-being, and the necessity for full inclusion of previously marginalized and disadvantaged groups and communities. Essential components of such assessments will be enhanced health surveillance employing linked longitudinal cohort studies that are fully representative of populations along with measurements of psychosocial and physiological AL as predictors of health outcomes. Stress is a nearly universal response to traumatic events, and individuals in disadvantaged communities are likely to experience higher levels of chronic stress. Working with health professionals, community leaders and community-based organizations could seize upon AL as a means of identifying people likely to be more affected by stress, circumstances prone to engender additional stress in their communities (e.g., chronic flooding, gentrification), and how to target interventions to reduce stress and thereby decrease health issues. These and mechanistic studies employing a variety of animal models are important areas for future study and action.

Conflict of interest statement

The authors declare no competing interests.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2022.105725.

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