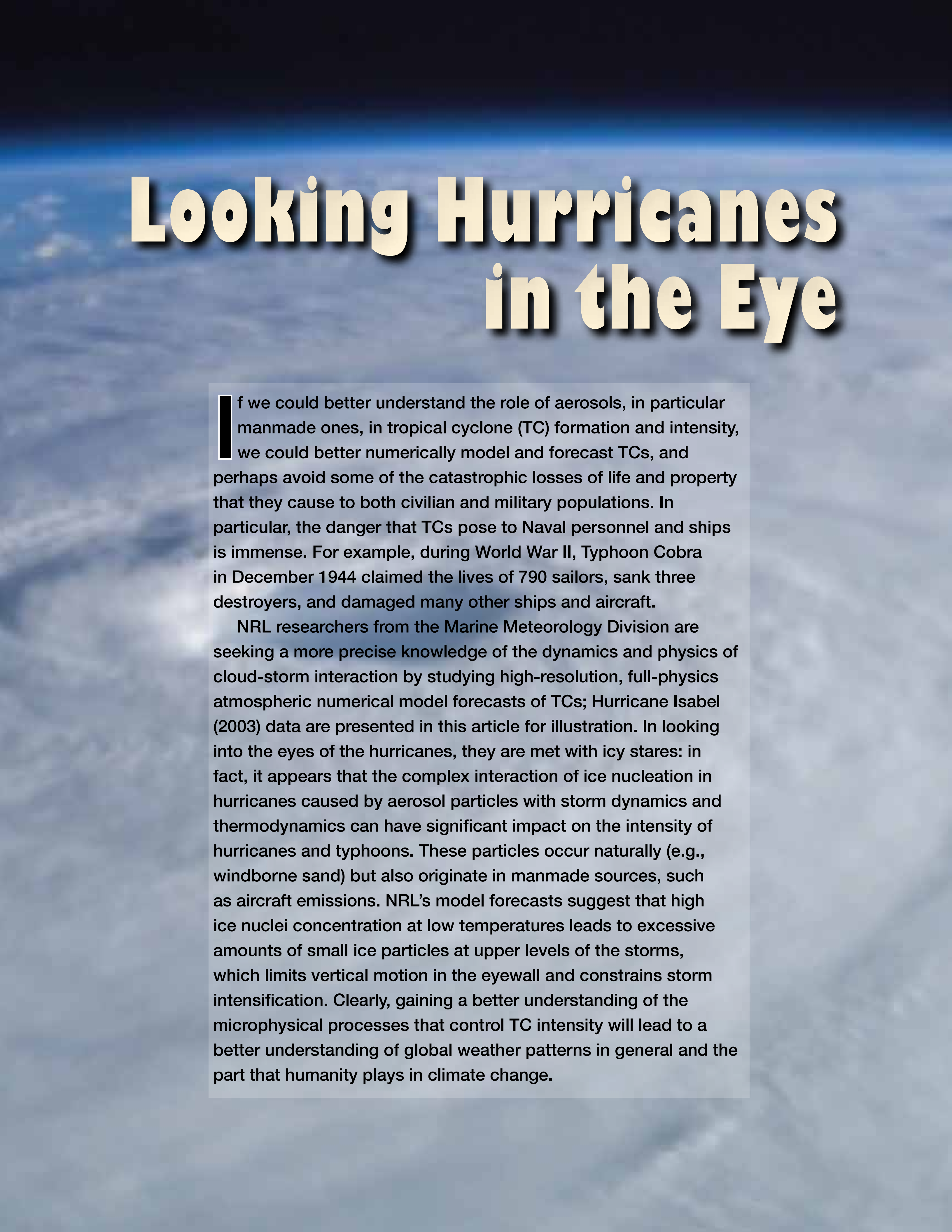

Looking Hurricanes in the Eye

If we could better understand the role of aerosols, in particular manmade ones, in tropical cyclone (TC) formation and intensity, we could better numerically model and forecast TCs, and perhaps avoid some of the catastrophic losses of life and property that they cause to both civilian and military populations. In particular, the danger that TCs pose to Naval personnel and ships is immense. For example, during World War II, Typhoon Cobra in December 1944 claimed the lives of 790 sailors, sank three destroyers, and damaged many other ships and aircraft.

NRL researchers from the Marine Meteorology Division are seeking a more precise knowledge of the dynamics and physics of cloud-storm interaction by studying high-resolution, full-physics atmospheric numerical model forecasts of TCs; Hurricane Isabel (2003) data are presented in this article for illustration. In looking into the eyes of the hurricanes, they are met with icy stares: in fact, it appears that the complex interaction of ice nucleation in hurricanes caused by aerosol particles with storm dynamics and thermodynamics can have significant impact on the intensity of hurricanes and typhoons. These particles occur naturally (e.g., windborne sand) but also originate in manmade sources, such as aircraft emissions. NRL's model forecasts suggest that high ice nuclei concentration at low temperatures leads to excessive amounts of small ice particles at upper levels of the storms, which limits vertical motion in the eyewall and constrains storm intensification. Clearly, gaining a better understanding of the microphysical processes that control TC intensity will lead to a better understanding of global weather patterns in general and the part that humanity plays in climate change.

The Impact of Ice Nuclei Concentration on Hurricane Modeling

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Uncertainties due to aerosol interactions with radiative and cloud processes are not only a prominent issue for climate change research, but may even have important consequences for tropical cyclones as well. Suspended particulates can convert into condensation and ice nuclei, which can impact cloud-radiation interactions as well as latent heat release, resulting in complex interactions with atmospheric dynamics, especially in strongly forced systems such as tropical cyclones. Using high-resolution, full physics atmospheric numerical model forecasts of Hurricane Isabel (2003), we demonstrate that the intensity and structure prediction of tropical cyclones is highly sensitive to the ice nuclei concentration. Excessive ice particles at upper levels directly limit the development of vertical motion in the eyewall and constrain the intensification of storms. An improved understanding of ice nucleation processes and their representation in numerical models is needed to fully address aerosol-cloud interactions in tropical cyclones, as well as issues related to tropical cyclone characteristics and climate change.

INTRODUCTION

Tropical cyclones (TCs), which include hurricanes in the Atlantic basin and typhoons in the Western Pacific, are one of the most destructive natural phenomena on Earth since they are often accompanied by severe winds, torrential rainfall, extreme ocean waves, storm surges, and flooding. Tropical cyclones have a huge societal impact through potentially catastrophic property damage and loss of life. Hurricanes and tropical storms accounted for 46.3% (or $137B) of all catastrophic losses from 1987 to 2006 according to the Insurance Information Institute. The potential impact of tropical cyclones on Navy operations can also be enormous. An extreme example is the infamous Typhoon Cobra, also known as Halsey's Typhoon after Admiral William Halsey, which struck the Pacific Fleet in December 1944 during World War II. Three destroyers were lost, and 790 sailors perished. During Hurricane Isabel of 2003, a total cost of $105.6 million was incurred for the sortie and return of 40 Navy ships and 150 airplanes (information provided by LT Anderson, Navy Maritime Forecast Center). The expeditionary capability of Navy operations and safety of Navy personnel require more accurate tropical cyclone forecasts, as emphasized recently by the Oceanographer of the Navy, RADM David Titley.[1]

Although there has been steady improvement in TC track prediction in the past two decades, there has been little progress in improving TC intensity and structure forecasts due to reasons ranging from lack of observations under high wind conditions to inaccurate representations of TC dynamics and physics in numerical weather prediction (NWP) models. One of the most contentious topics in the climate change debate is the climatological frequency and intensity of TCs in a globally warmed climate. While examination of long-term observational records has sometimes led to contradictory conclusions, unfortunately the current state of the art of numerical models is not yet sophisticated enough to reach a physics-based determination.

Recent research, including work being led at NRL, points to the importance of processes associated with small ice particles within the storms that have a strong influence on TC intensity and structure. Improved understanding of these key processes governing the ice particles and their complex interplay with cloud droplets, and of the cooling and heating impacts from microphysical processes in the eyewall and surrounding areas, is essential for accurate hurricane intensity and structure forecasts. Moreover, recent studies (for instance, see Ref. 2) underscore the important role of aerosols of both natural and anthropogenic origin in cloud ice and precipitation processes, and in particular their impact on hurricane intensity and structure changes. The research described here is focused on the sensitivity of hurricane intensity and structure forecasts to the ice nucleation processes, more specifically, the ice nuclei concentration, using the Navy's recently developed COAMPS®*-TC (Coupled Ocean and Atmosphere

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*COAMPS is a trademark of the Naval Research Laboratory.

Mesoscale Prediction System – Tropical Cyclone), which is a limited area model that has been designed to predict the TC track, intensity, and structure.

ROLE OF ICE NUCLEI

Under most atmospheric conditions, ice particles form by heterogeneous nucleation, which occurs via four different pathways: deposition, condensation freezing, immersion, and contact freezing. Aerosol particles (AP) are needed to act as ice nuclei (IN) in all four major modes. Any given AP of a certain size and chemical property can be IN for any one or all four of the nucleation modes under certain temperature and moisture conditions. One main source of IN is mineral dust, which often originates from the Sahara and Gobi Deserts and can be transported over great distances. Emissions from aircrafts, such as soot, can also be very efficient IN when the particle surface contains chemicals conducive for hydrogen bonds with water molecules. Despite decades of efforts in advancing IN measurements, and examination of nucleation processes through field campaigns, laboratory tests, and theoretical work, fundamental discrepancies remain in the IN characteristics derived from experimental and theoretical considerations (see, for example, Ref. 3).

Due to the difficulty in explicitly representing IN and their complicated interactions with the atmospheric environment in NWP models, the IN concentration typically is parameterized using a simple function of temperature (and moisture in some approaches). The complexity of the nucleation processes and the lack of observations distinguishing various ice nucleation pathways lead to large uncertainties in IN formulations, as evidenced by the nearly dozen IN formulations commonly employed in NWP models. Two of the most frequently used formulations are based on the research of Fletcher (1962)[4] and Cooper (1986).[5] Fletcher's formulation (shown in red in Fig. 1) was derived after synthesizing IN observations at a dozen locations worldwide. The observed IN counts, from which the Fletcher formulation was derived, vary by more than an order of magnitude between locations, underscoring the variability of IN characteristics. Cooper's formulation (shown in blue in Fig. 1) was based on in situ measurements of ice crystals in continental clouds. Note that the variability between these two formulations exceeds an order of magnitude. The Cooper formulation produces as much as two orders of magnitude more IN at warmer temperature (>-20 °C) than does Fletcher's, whereas Fletcher's has more than an order of magnitude more IN at colder temperatures. The differences between the two sets of measurements represent variations in the IN concentrations broadly corresponding to clean or polluted environments. Also evident in Fig. 1 is the implied temperature threshold, below which IN no longer increases with decreasing temperature. Observations of ice nucleation at cold temperatures (<-30 °C) are rare and a temperature threshold is often introduced in NWP models to reduce excessive ice particle concentration at very low temperatures. The uncertainty related to IN calculations is exacerbated when significant differences in the temperature threshold exist not only between the Fletcher and Cooper formulations, but also among the similar formulations implemented in various other microphysics representations. The differences among the various formulations can be as large as 13 K.

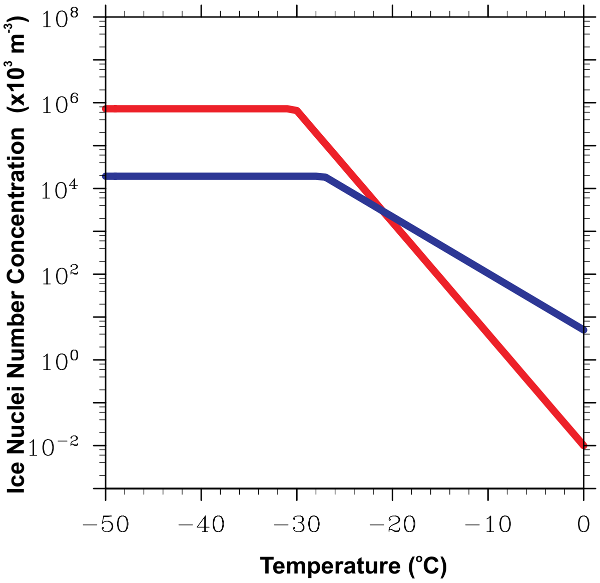

FIGURE 1
Number of ice-forming nuclei (10^3 m^{-3}) as a function of temperature from the Cooper (blue) and Fletcher (red) formulations.

NUMERICAL MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

The COAMPS-TC system is based on COAMPS,[6] which is under continuous development at the Naval Research Laboratory and has been used by Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC) for operational forecasting since 1998. Representations of physical processes within COAMPS-TC include: sub-grid-scale convective processes; cloud microphysical processes with prognostic equations for the mass conservation of cloud droplets, ice particles, rain, snow, graupel, and drizzle; radiative transfer processes for shortwave and longwave radiation; surface layer flux processes, and planetary boundary layer mixing. The basic COAMPS model has also been used for numerous studies of various weather phenomena at a wide range of scales from several hundred kilometers down to less than 50 m.

We performed a large number of COAMPS-TC forecast experiments for Atlantic TCs during 2002 to 2005 to further examine ice microphysical processes. Hurricane Isabel (2003) is selected here to illustrate the sensitive impact of IN on hurricane model forecasts. Hurricane Isabel reached category five on the Saffir-Simpson scale during the 120-hour forecast period starting from 0000 UTC 7 September. A triply nested grid configuration with the innermost domain following the storm motion is used. The grid spacing in the moving nest is 5 km and there are 40 vertical levels from the surface to approximately 30 km height. The innermost domain exclusively relies on the explicit microphysics predictive equations for cloud and precipitation processes, without applying a sub-grid-scale convection representation, which is applied in the outer two meshes, as commonly done in NWP models when the grid increment exceeds 5 to 10 km. Thus, the impact of varying the IN formulation on clouds and precipitation within the innermost mesh can be isolated in these experiments.

NUMERICAL MODEL RESULTS AND EVALUATION

The time evolution of the intensity of Hurricane Isabel derived from the 5-km-resolution grid forecast clearly indicates that the storm's intensity varies significantly between the forecasts using the Fletcher and Cooper IN formulations [Fig. 2(a)]. For example, the maximum surface wind using the Cooper formulation is 18 m s^{-1} stronger [Fig. 2(a)] than the experiment using the Fletcher formulation near the end of the 120-hour forecast. The minimum surface central pressure differs by 20 hPa after 120-hour forecasts [Fig. 2(b)]. Furthermore, the IN impact on storm structure is evident, especially during the late forecast hours. At the 102-hour forecast time, the experiment using the Cooper formulation produces a strong storm [Fig. 3(b)] with a well-organized inner-core structure, including up to 3 m s^{-1} upward vertical motion at mid levels (4 to 6 km height) in the hurricane eyewall and high values (up to 55 dBZ) of model-derived radar reflectivity. This narrow and strong mid-level updraft apparent in the forecast using the Cooper formulation is reduced to 1 m s^{-1} and widened to a horizontal distance of about 100 km in the forecast using the Fletcher formulation [Fig. 3(a)]. Another pronounced distinction between these two forecasts is the ice concentration distribution at upper levels (10 to 15 km). Corresponding to the high IN concentration at colder temperatures (Fig. 1), the forecasts using the Fletcher approach produce an order of magnitude more ice particles than the Cooper formulation at the upper levels where temperature is colder than -20 °C.

Given this apparent sensitivity of TC intensity forecasts to differences in the IN formulations, we carried out additional numerical experiments to assess the sensitivity of model forecasts to the IN concentration. Since the forecast using the Cooper formulation captures the observed storm intensity relatively well (see Fig. 2), we specify two new IN concentrations (Fig. 4) based on the Cooper formulation, with one (IN×10) having ten times greater IN concentration (New2,

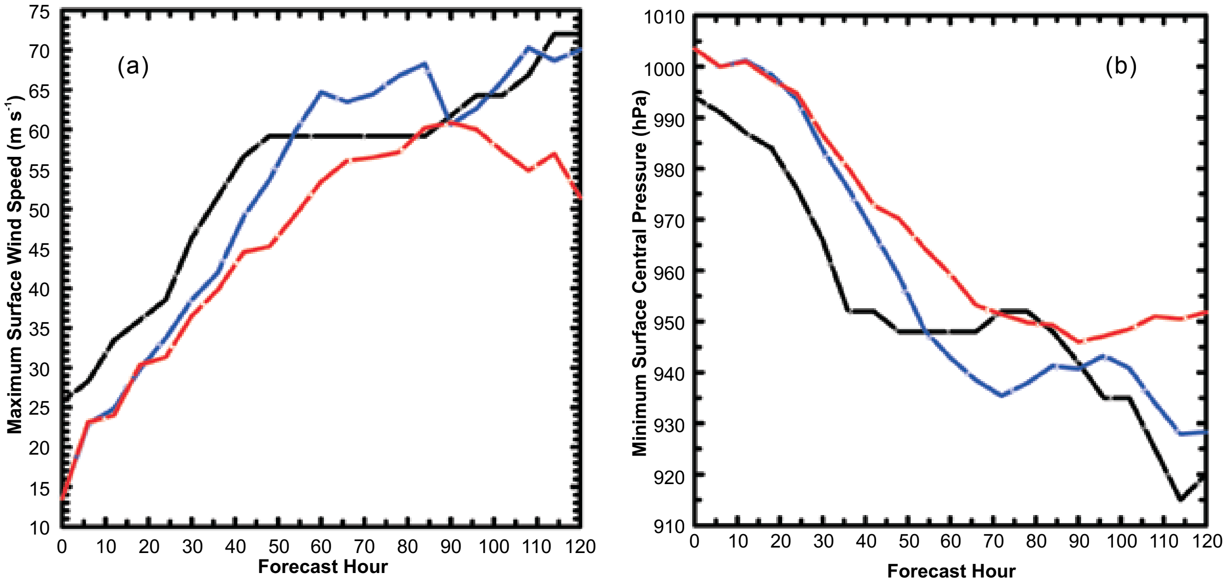

FIGURE 2
COAMPS-TC forecasts of Hurricane Isabel (2003) intensity using the Cooper (blue lines) and Fletcher (red lines) IN formulations (see Fig. 1) showing maximum surface winds (a) and minimum surface central pressure (b) over the 120-hour forecast period starting from 0000 UTC 7 September 2003. The black lines are for observed intensity from the best track data.

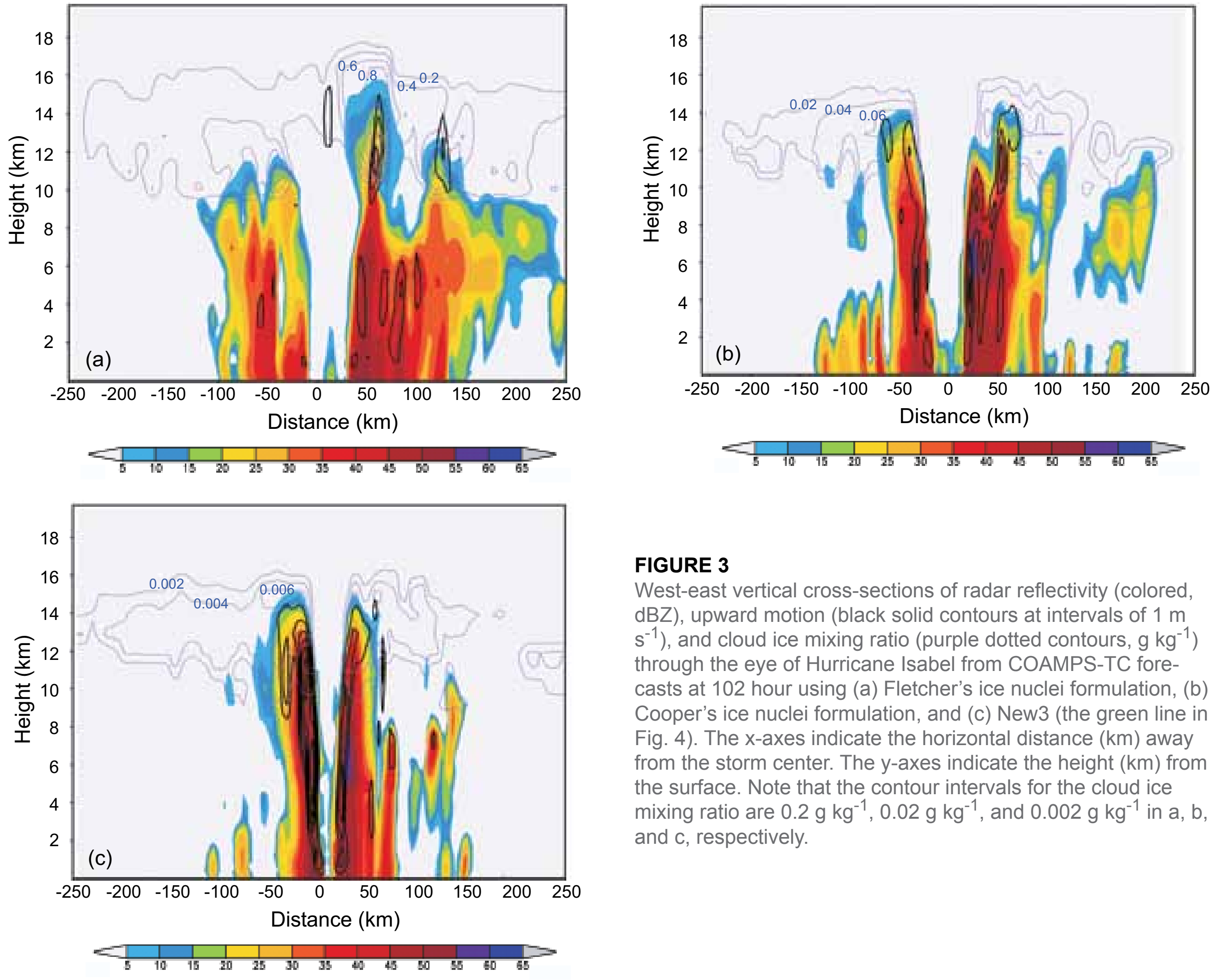

FIGURE 3
West-east vertical cross-sections of radar reflectivity (colored, dBZ), upward motion (black solid contours at intervals of 1 m s^{-1}), and cloud ice mixing ratio (purple dotted contours, g kg^{-1}) through the eye of Hurricane Isabel from COAMPS-TC forecasts at 102 hour using (a) Fletcher's ice nuclei formulation, (b) Cooper's ice nuclei formulation, and (c) New3 (the green line in Fig. 4). The x-axes indicate the horizontal distance (km) away from the storm center. The y-axes indicate the height (km) from the surface. Note that the contour intervals for the cloud ice mixing ratio are 0.2 g kg^{-1}, 0.02 g kg^{-1}, and 0.002 g kg^{-1} in a, b, and c, respectively.

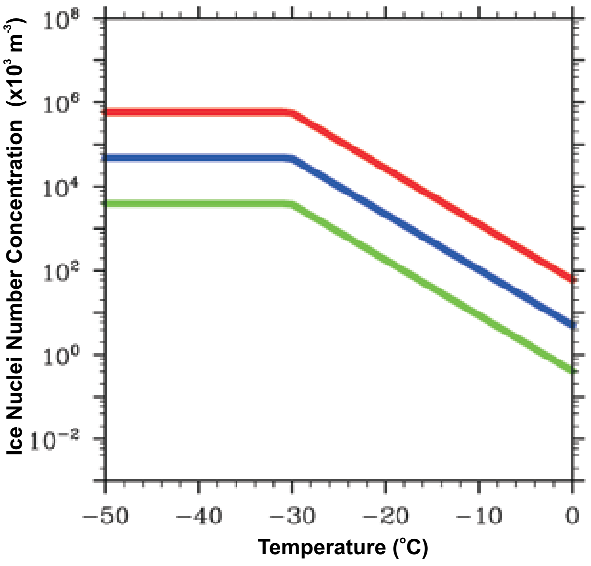

FIGURE 4
Number of ice-forming nuclei (10^3 m^{-3}) as a function of temperature from the Cooper (blue), New2 (red), and New3 (green) formulations.

TABLE 1 — The Minimum Surface Central Pressure (SLP) and Surface Maximum Wind (MAXW) of the 120-hour COAMPS-TC Forecasts Using the Cooper, New2, and New3 IN Formulations

	Cooper	**New2**	**New3**
Minimum SLP (hPa)	926	932	911
MAXW (m s^{-1})	70	68	76

red line) and the other experiment (IN/10) with IN reduced by a factor of ten than what Cooper's would yield at the same temperature (New3, green line). Table 1 lists the differences in the storm peak intensity among these tests. The IN×10 experiment produces a storm that has similar intensity (Table 1) and structure (not shown) as the test using the original Cooper formulation. The similarity between the Cooper and the IN×10 experiment suggests that for a given environmental condition (i.e., temperature, moisture, and winds), the storm system is not particularly sensitive to the increased IN concentration and indicates that perhaps a "saturated" state is achieved with respect to IN. On the other hand, the forecast storm using the IN/10 configuration deviates substantially from the storm evolution relative to the control Cooper forecast, not only with regard to the intensity (see Table 1), but also interestingly the storm structure as well [Fig. 3(c)]. Consistent with the IN specification and our expectations, the cloud ice at upper levels in the IN/10 storm is about 10 times less than that in the Cooper storm and about 100 times less than the storm using the Fletcher formulation. While the minimum surface central pressure and surface maximum wind speed values from the IN/10 forecasts during the first 36 forecast hours are very similar to those in the control experiment using the Cooper formulation, the cloud ice in the IN/10 experiment is 10 times less that in the control. The persistently reduced concentration of cloud ice in IN/10 has an important bearing on the subsequent storm development. The IN/10 storm eventually obtains more vigorous convection at mid levels in the eyewall, with updrafts exceeding 6 m s^{-1} (twice as much as that in the control forecast using the Cooper formulation) and similarly stronger upward vertical motion at upper levels (11 to 13 km) as well. The inner core size of IN/10 decreases significantly from that of the storm using the control Cooper formulation, and exhibits symmetric structures with narrower updrafts and high radar reflectivity on both sides of the storm.

A budget analysis reveals that the large mass of excessive cloud ice at upper levels using the Fletcher formulation limits the vertical motion in the inner core region and directly constrains the development of updrafts, as well as the intensification of the storm. Another possible reason for the weakened storm using the Fletcher formulation is that the widespread ice particles at upper levels [see Fig. 3(a)] can potentially initiate precipitation in the region outside the eyewall. The aerosol-invigorated convection in the outer region may in turn lead to decreased graupel and snow production in the eyewall [indicated by the lower radar reflectivity in the eyewall in Fig. 3(a)] and further reduce the associated latent heat release in the inner core, consistent with recent studies (see, for example, Ref. 2).

SUMMARY AND DISCUSSION

The primary objective of this research is to evaluate the impact of ice nuclei concentration on hurricane intensity and structure derived from numerical model forecasts. Our model forecasts of Hurricane Isabel clearly suggest that high IN concentration at low temperature (<-25 °C) leads to excessive ice particles at upper levels in the hurricane inner core region, resulting in much weakened updrafts, reduced near-surface wind speeds, and a broader inner core of the hurricane. In the outer regions of the storm, denser and more widespread ice clouds form when high IN concentration exists. It follows from this study that aerosols, acting as ice nuclei, can have a profound impact on the development of hurricanes and weather in general. Our results suggest there indeed is a plausible link between concentrations of atmospheric particulates generated by either natural or anthropogenic sources and TC intensity, which highlights the complex and multifaceted nature of the interdependence between TC characteristics and climate change. As we continue to advance our ability to numerically predict tropical cyclones, in part through the inclusion of more sophisticated and truthful representations of microphysical processes, we expect to gain much-needed insight into the mechanisms that control the intensity of tropical cyclones, as well as a new understanding of tropical cyclone characteristics in the changing global environment.

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[Sponsored by ONR]

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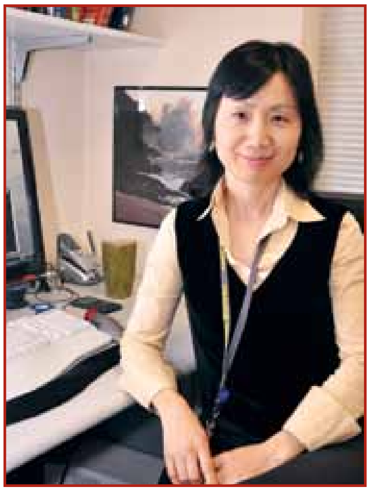
THE AUTHORS



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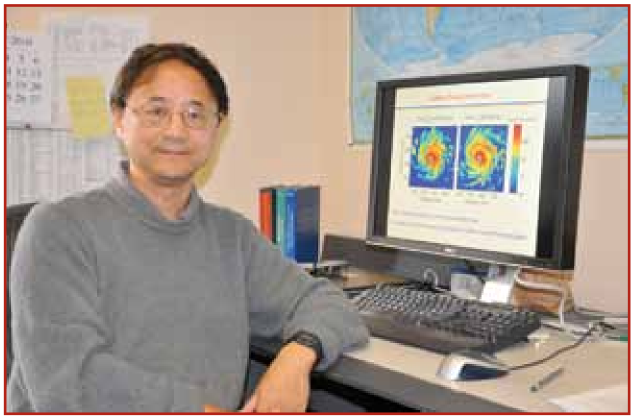

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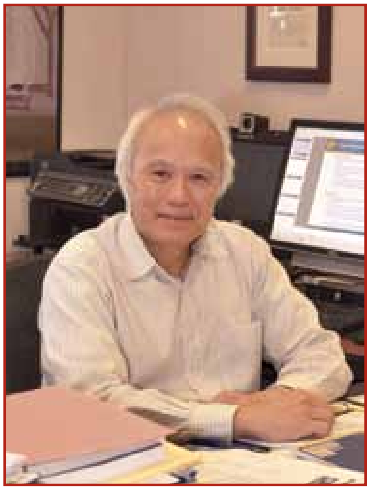

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