Chapter 10

Models for Multiscale Interactions. Part II: Madden–Julian Oscillation, Moisture, and Convective Momentum Transport

ANDREW J. MAJDA

Department of Mathematics, and Center for Atmosphere Ocean Science, Courant Institute of Mathematical Sciences, New York University, New York, New York

SAMUEL N. STECHMANN

Department of Mathematics, and Department of Atmospheric and Oceanic Sciences, University of Wisconsin–Madison, Madison, Wisconsin

ABSTRACT

It is well known that the envelope of the Madden–Julian oscillation (MJO) consists of smaller-scale convective systems, including mesoscale convective systems (MCS), tropical cyclones, and synoptic-scale waves called "convectively coupled equatorial waves" (CCW). In fact, recent results suggest that the fundamental mechanisms of the MJO involve interactions between the synoptic-scale CCW and their larger-scale environment (Majda and Stechmann). In light of this, this chapter reviews recent and past work on two-way interactions between convective systems—both MCSs and CCW—and their larger-scale environment, with a particular focus given to recent work on MJO–CCW interactions.

1. Introduction

In this chapter, the multiscale hierarchy of organized convection will be divided into three broad categories: (i) the MJO on planetary spatial scales (roughly 20 000 km) and intraseasonal time scales (roughly 40 days) (Lau and Waliser 2005; Zhang 2005), (ii) convectively coupled equatorial waves (CCW) on equatorial synoptic scales (roughly 2000 km and 4 days) (Kiladis et al. 2009), and (iii) MCS on mesoscales (roughly 200 km and 0.4 days) (Houze 2004). This hierarchy has a remarkable multiscale structure: the MJO is an envelope of smaller-scale CCW, and, in turn, the CCW are envelopes of smaller-scale MCS. Figure 10-1 illustrates the structure of a generic large-scale envelope with smaller-scale fluctuations embedded within it. For such a multiscale envelope, one can imagine three scenarios for its physical mechanisms: (i) Does the envelope drive the fluctuations within it? (ii) Do the fluctuations drive the large-scale envelope? (iii) Or do the two evolve cooperatively? This situation is reminiscent of the classic conundrum: Which came first: the chicken or the egg? In atmospheric science, such questions are most familiar from contexts such as midlatitude eddies and jets. Here, instead, the focus is on the tropical case described above, and the evidence will suggest that, in fact, there are cooperative interactions between the envelopes and the fluctuations within them.

2. The chicken–egg question: Interactions between convective systems and their larger-scale environment

In this section, we review recent and past results on convection–environment interactions. MCS–environment interactions are reviewed first in order to set the stage for the relatively new topic of CCW–environment interactions and in order to highlight their similarities and differences.

It is well known that MCS can have important effects on the larger-scale atmospheric state in which they exist (Houze 2004). For example, precipitation and vertical transports of temperature and moisture can significantly

Corresponding author address: Samuel Stechmann, Department of Mathematics, University of Wisconsin–Madison, 480 Lincoln Drive, Madison, WI 53706.
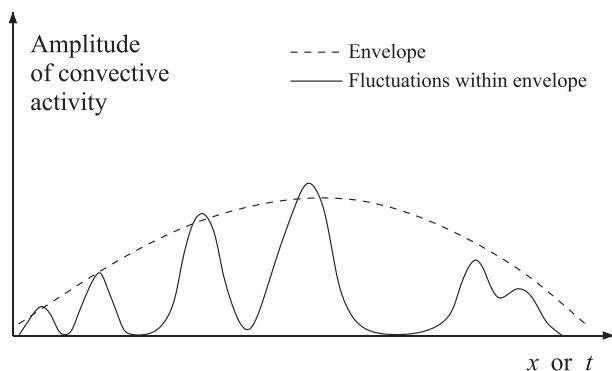E-mail: stechmann@wisc.edu

FIG. 10-1. A large-scale envelope with fluctuations embedded within it.

alter the larger-scale thermodynamic environment. A less-understood effect of MCS on their larger-scale environment is convective momentum transport (CMT). A pervasive aspect of this is the idea of "cumulus friction"; however, many studies have also shown that the CMT of some MCS can actually accelerate the background wind (Wu and Yanai 1994; LeMone and Moncrieff 1994; Tung and Yanai 2002a,b). On the other hand, these interactions also proceed in the opposite direction: the background state—including the wind shear and moist thermodynamic state—affects the MCS that form within it. The intensity of an MCS is related to the environmental thermodynamic state, and the vertical wind shear du/dz determines the propagation direction and morphology of MCS (Barnes and Sieckman 1984; LeMone et al. 1998; Liu and Moncrieff 2004).

On larger scales than MCS are the synoptic-scale phenomena known as CCW (Kiladis et al. 2009). With typical wavelengths of 2000–8000 km and periods of 2–10 days, CCW are the dominant synoptic-scale weather features in many regions in the tropics, but they are less understood than the smaller-scale MCS. Just as MCS interact with their larger-scale environment, so do CCW. However, CCW–environment interactions are in a relatively primitive stage of understanding.

On the one hand, one might suspect that CCW can affect their larger-scale environment as MCS do. Some results using diagnostic models for the CCW have demonstrated that this is true [see Haertel and Kiladis (2004), Biello et al. (2007), and references therein]. For example, CCW can act as heat sources and moisture sinks for their environment. Also, since they have tilts in the vertical/zonal direction (Takayabu et al. 1996; Straub and Kiladis 2003), CCW can transport momentum to larger scales. That is to say, eddy flux divergences can accelerate or decelerate the mean flow, where the CCW are the "eddies" in this context. This has important implications

for the MJO, as shown in the diagnostic multiscale models of Biello and Majda (2005) and Biello et al. (2007). They demonstrate that the westerly jet that appears during the westerly wind burst stage of the MJO can be driven by momentum transports from synoptic-scale CCW.

On the other hand, one might also suspect CCW–environment interactions to occur in the other direction; that is, one might suspect that the background state—including the background wind and moist thermodynamic states—can affect the CCW that form within it. Unfortunately, while several studies have documented the properties of CCW, few have documented them in different, distinct background environments [exceptions to this include Roundy and Frank (2004) and Yang et al. (2007)]. Besides observations, computer simulations of CCW have presently offered little insight into CCW–environment interactions, since general circulation models (GCMs) do not adequately capture CCW (Lin et al. 2006), and simulations of CCW with cloud-resolving models (CRMs) are challenging [but not impossible: see Grabowski and Moncrieff (2001), Tulich et al. (2007), and the discussion below]. One promising method for numerical simulations of CCW is the so-called multicloud model in the recent work of Khouider and Majda (2006, 2008), which has been successful in capturing observed features of CCW and in explaining their physical mechanisms.

Numerical simulations with the multicloud model offer some of the first glimpses of two-way CCW–environment interactions. Majda and Stechmann (2009a) show that the background vertical wind shear can favor either eastward- or westward-propagating CCW, which is analogous to the effect of wind shear on MCS as discussed above (although the details of the two cases are different). Also, because of their vertical/zonal tilts (Takayabu et al. 1996; Straub and Kiladis 2003), CCW can transport momentum to larger scales and alter the mean winds. Therefore, the combination of these effects allows for convectively coupled wave–mean flow interaction with dynamical two-way interactions between CCW and the background vertical shear. In this dynamical setting, Majda and Stechmann (2009a) showed that a low-level westerly jet, like that seen in the westerly wind burst stage of the MJO, can be driven by momentum transports due to convectively coupled Kelvin waves, which are often observed in the envelope of the MJO (Nakazawa 1988; Masunaga et al. 2006). These basic CMT features can also be illustrated using simple ordinary differential equations for wave amplitudes and the mean wind (Stechmann et al. 2013). Furthermore, Khouider et al. (2012b) investigated competing CMT effects due to multiscale waves. Using different MJO phases for the background environment, they compared the CMT

due to a convective envelope (such as a convectively coupled wave) and the convective elements embedded within the envelope (such as squall lines).

Besides CCW–environment interactions involving momentum, one might also expect CCW to interact with their larger-scale moist thermodynamic environment. Indeed, the recent model of Majda and Stechmann (2009b) suggests that the essential physical mechanisms of the MJO involve such interactions.

3. The MJO's "skeleton" and "muscle"

The fundamental mechanism of the MJO proposed by Majda and Stechmann (2009b, 2011) involves neutrally stable interactions between (i) planetary-scale lower-tropospheric moisture anomalies and (ii) the planetary-scale envelope of smaller-scale convective activity, which can include both CCW and MCS. Using a simple dynamical model with these features, they captured all of the following fundamental features (i.e., the skeleton) of the MJO: (i) peculiar dispersion relation of roughly $dw/dk = 0$, (ii) slow eastward phase speed of roughly $5 \, \mathrm{m \, s^{-1}}$, and (iii) horizontal quadrupole vortex structure (Hendon and Liebmann 1994; Wheeler and Kiladis 1999). The prediction of all of these features is strong evidence that CCW–moisture interactions are the essential physical mechanism of the MJO.

The basis for the mechanisms mentioned above comes from observations, theory, and modeling studies. On the one hand, CCW activity affects the heat and moisture budgets of the MJO through the planetary-scale envelope of its heating and drying. On the other hand, the moist thermodynamic environment regulates the growth/decay of CCW activity (Khouider and Majda 2008) in a way similar to the effects of a background wind shear on CCW (Majda and Stechmann 2009a). This is also suggested by observations that show the maximum of lower-tropospheric water vapor leading the maximum in convective activity (Kiladis et al. 2005), which indicates that the positive (negative) low-level water vapor anomalies have a tendency to increase (decrease) the envelope of CCW and MCS activity.

These CCW–moisture interactions are at the heart of the model of Majda and Stechmann (2009b, 2011) that produces the MJO's skeleton as described above. However, the MJO has other features beyond this basic skeleton, and we refer to these additional features as the MJO's muscle. One aspect of the MJO's muscle is its westerly wind burst, which can be driven by momentum transports of CCW as described in the previous section. Other asymmetries that fall within the realm of the MJO's muscle are potentially due to other upscale fluxes from synoptic scales and variations in surface heat fluxes (Sobel et al. 2010).

4. Implications for GCMs

Given the wide range of interactions involved in the hierarchy of organized tropical convection, it is maybe not surprising that GCMs, which must parameterize an important subset of the hierarchy, struggle with capturing CCW and the MJO (Moncrieff and Klinker 1997; Lin et al. 2006). With grid spacings of roughly 100 km, GCMs can at best hope to capture convection on scales of roughly 1000 km and larger (i.e., CCW and the MJO), assuming that about 10 grid points are needed to properly resolve a given feature. This also implies that features with scales of 100–1000 km and smaller must be parameterized; MCS fall within this category but are often ignored in parameterizations. These two problems—properly representing CCW and parameterizing MCS—are crucial to improving the MJO and the hierarchy of organized convection in GCMs.

A convective parameterization that captures realistic CCW is the multicloud parameterization of Khouider and Majda (2006, 2008), which includes several features that are not standard among contemporary convective parameterizations. The key aspect of this parameterization is the representation of three different cloud types: congestus, deep convection, and stratiform clouds (Houze 2004; Johnson et al. 1999). Each of these different phases of convection plays a different role in the heat and moisture budgets, and it is important to include all three phases rather than just deep convection (Haertel and Kiladis 2004; Khouider and Majda 2006, 2008). Another important component is convective triggering, for which the mid- and lower-tropospheric moisture plays a key role. While the multicloud parameterization has been developed using simplified dynamical models, it is currently being included in a GCM. Also, a stochastic version is being developed that includes stochastic transitions among different phases of convection (congestus, deep convection, and stratiform) (Khouider et al. 2010).

The effect of unresolved MCS on resolved GCM dynamics can occur in several ways, one of which is CMT. It has been recognized that CMT can either accelerate or decelerate the mean wind (Wu and Yanai 1994; LeMone and Moncrieff 1994), and representations of this feature have been included in parameterizations that have improved climatological-scale circulations (Wu et al. 2007; Richter and Rasch 2008). However, observations also show that the acceleration/deceleration due to CMT occurs in intense, intermittent bursts (Tung and Yanai 2002a,b), and that including this intermittency should be important for the variability of resolved convection. A promising method for including the intermittent aspects of unresolved CMT is to use a

stochastic CMT parameterization (Majda and Stechmann 2008; Khouider et al. 2012a).

The general principles described above—different phases of convection and momentum transports—also appear to be important for the specific case of capturing the MJO in GCMs. In terms of different phases of convection, the congestus phase of convection appears to be important for moistening the lower troposphere during the MJO's suppressed stage (Kikuchi and Takayabu 2004; Tian et al. 2006). However, GCMs do not appear to properly represent congestus clouds and the accompanying moistening effects. It is possible that parameterizations with minimum entrainment parameters, which have improved the strength of intraseasonal variability in some GCMs, are employing a surrogate for congestus clouds and lower-tropospheric moistening (Tokioka et al. 1988; Sobel et al. 2010). Besides congestus clouds, another important physical effect in the multicloud model that is largely absent in contemporary GCMs is unsaturated downdrafts in the stratiform region, which are important for cooling and drying the lower troposphere. In terms of the second general principle—momentum transports—a stochastic parameterization of unresolved CMT, such as that of Majda and Stechmann (2008), should help increase the variability of CCW and the MJO, which tends to be significantly lower than in observations (Lin et al. 2006).

It is possible that lessons for GCMs can be learned from CRM simulations of multiscale convection, since CRMs are able to represent a CCW envelope and the MCS within it, whereas GCMs struggle to capture the MJO envelope and the CCW within it. For instance, the role of CMT and momentum damping can be seen in CRM simulations of CCW. The simulations of Grabowski and Moncrieff (2001) employ (parameterized) weak momentum damping with a time scale of 24 h, and the results show that resolved CMT from MCS plays an important role in driving the CCW envelope. On the other hand, the simulations of Tulich et al. (2007) employ (parameterized) stronger momentum damping with a time scale of 4 h, and they find little role of resolved CMT in driving the CCW envelope; instead, the key mechanism involves interactions between MCS and gravity waves generated by the MCS (Mapes 1993; Tulich and Mapes 2008; Stechmann and Majda 2009). Other CRM simulations of Held et al. (1993) show two extreme cases with (i) no CMT allowed and (ii) no momentum damping, and the results are completely different in the two cases. Given this variety of results, it is likely that parameterized momentum sources in GCMs strongly affect the resolved waves—that is, CCW and the MJO—and the simulated mechanisms behind them.

5. Summary

Recent research suggests that the fundamental mechanisms of the MJO involve interactions between CCW and their larger-scale environment (Majda and Stechmann 2009a,b, 2011), and this chapter is a review of these interactions (see also Khouider et al. 2013). Implications for GCMs were also discussed, both in terms of general principles for subgrid-scale parameterization and in terms of the MJO specifically. These ideas should be useful for improving our theoretical understanding and numerical simulations of the MJO.

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