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Well-posedness and convergence of entropic approximation of semi-geostrophic equations

Guillaume Carlier*, Hugo Malamut†

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Abstract

We prove existence and uniqueness of solutions for an entropic version of the semi-geostrophic equations. We also establish convergence to a weak solution of the semi-geostrophic equations as the entropic parameter vanishes. Convergence is also proved for discretizations that can be computed numerically in practice as shown recently in [6].

Keywords: optimal transport, entropic optimal transport, semi-geostrophic equations.

MS Classification: 49Q22, 35D30, 35Q35.

1 Introduction

The semi-geostrophic equations are used in meteorology to describe frontogenesis for large scale atmospheric flows. Initially proposed by Eliassen [18] in the late 1940s and subsequently developed by Hoskins [21] and Cullen, see [12], [13], [14], they have gained a lot of attention by mathematicians because of their connections with optimal transport theory. The seminal work of Brenier [8] indeed enabled Benamou and Brenier [5] to define a notion of weak solutions and establish the existence of such solutions. This was later generalized by Loeper [24] in the framework of measure-valued

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solutions (also see Feldman and Tudorascu [19, 20]). It is also worth mentioning here that Ambrosio and Gangbo [3] developed a general and self-contained theory of Hamiltonian systems in the Wasserstein space which contains semi-geostrophic equations as a special case. Regarding stronger notions of solutions, thanks to the deep regularity theory for the Monge-Ampère equation, Ambrosio, Colombo, De Philippis and Figalli were able to obtain Eulerian solutions in the two-dimensional periodic case [1] and for convex three-dimensional domains [2].

Given Ω a Lipschitz bounded open subset of $\mathbb{R}^3$, and α_0 a Borel measure on $\mathbb{R}^3$ with total mass $|\Omega|$ the semi-geostrophic system reads as the coupling of the continuity equation

$$\partial_t \alpha + \operatorname{div}(\alpha J(\operatorname{id} - \nabla \psi)) = 0, \quad \alpha(0, \cdot) = \alpha_0, \quad \text{with } J := \begin{pmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (1.1)$$

with the Monge-Ampère equation

$$\det(D^2 \psi_t) = \alpha_t, \quad \psi_t \text{ convex.} \quad (1.2)$$

Before going further, let us briefly explain the origin of (1.1)-(1.2), we refer to [12], [13] [14] and the references therein for a modern and complete exposition and a derivation from incompressible Euler equations with a large Coriolis force. The starting point is the following system

$$\begin{cases} D_t \mathbf{v}^g + \nabla p = -J\mathbf{v} + \theta e_3, & \operatorname{div}(\mathbf{v}) = 0, & \text{in } (0, \infty) \times \Omega \\ \mathbf{v}^g = J\nabla p, & D_t \theta = 0, & \text{in } (0, \infty) \times \Omega, \\ \mathbf{v} \cdot \nu_\Omega = 0, & & \text{on } (0, \infty) \times \partial\Omega, \quad p(0, \cdot) = p_0, \end{cases}$$

where $D_t = \partial_t + \mathbf{v} \cdot \nabla$ denotes the convective derivative, $e_3 = (0, 0, 1)^T$ is the vertical direction and ν_Ω denotes the outward unit normal to $\partial\Omega$. Note that the first equation enables one to relate the pressure p to the *buoyancy* θ through the simple relation $\partial_3 p = \theta$ and that the so-called semi-geostrophic balance equation $\mathbf{v}^g = J\nabla p$ imposes that the *semi-geostrophic velocity field* $\mathbf{v}^g$ is horizontal. Cullen's stability criterion [14] further requires that

$$P_t(x) = p_t(x) + \frac{1}{2}(x_1^2 + x_2^2)$$

is convex. Substituting $\mathbf{v}^g = J\nabla p$ in the first equation of the system yields

$$D_t \nabla P = J\nabla p = J(\nabla P - \operatorname{id}).$$

Let us then denote by $(t, x) \mapsto X_t(x)$ the flow of $\mathbf{v}$. This flow remains in the physical domain Ω (since $\mathbf{v}$ is tangential to $\partial\Omega$) and is measure preserving,

i.e. $X_{t\#}\mathcal{L}_\Omega = \mathcal{L}_\Omega$ where $\mathcal{L}_\Omega$ denotes the Lebesgue measure on Ω (since $\operatorname{div}(\mathbf{v}) = 0$). At least formally, we have

$$\begin{aligned}\partial_t \nabla P_t(X_t(x)) &= J(\nabla P_t(X_t(x)) - X_t(x)) \\ &= J(\operatorname{id} - \nabla P_t^*)(\nabla P_t(X_t(x)))\end{aligned}$$

where P_t^* is the Legendre transform of P_t . So if we set $\alpha_t := \nabla P_{t\#}\mathcal{L}_\Omega$ and $\psi_t := P_t^*$ (so that $\nabla \psi_t = (\nabla P_t)^{-1}$ and $\mathcal{L}_\Omega = \nabla \psi_{t\#}\alpha_t$ if ∇P_t is invertible and smooth), the semi-geostrophic system reads as the coupling of the continuity equation (1.1) (with initial condition $\alpha_0 = \nabla P_{0\#}\mathcal{L}_\Omega$) with the Monge-Ampère equation (1.2). Note that (1.1)-(1.2) is a reformulation of the initial semi-geostrophic system in *semi-geostrophic* coordinates i.e. after the change of variables $x \mapsto \nabla P_t(x)$. Conversely, note that (again formally) from a solution of (1.1)-(1.2) one recovers $\nabla P = \nabla \psi^*$, θ by $\theta = \partial_3 p = \partial_3 P$, $\mathbf{v}^g = J\nabla p$, and the velocity $\mathbf{v}$ by

$$\mathbf{v}_t(x) = \partial_t \nabla \psi_t(\nabla P_t(x)) + (D^2 \psi_t(\nabla P_t(x)))J(\nabla P_t(x) - x).$$

In general, ψ_t and P_t may fail to be smooth or strongly convex so that the previous computations only remain formal and one has to resort to some notion of weak solution, following the seminal optimal transport approach of Benamou-Brenier [5] (which will be recalled in section 2) based on the fact that ∇P_t is the optimal transport from $\mathcal{L}_\Omega$ to α_t .

The present paper is motivated by recent research on optimal transport methods to numerically solve semi-geostrophic equations. On the one hand, in the spirit of the geometric approach pioneered by Cullen and Purser [14], Bourne, Egan, Pelloni and Wilkinson proposed a semi-discrete optimal transport strategy [7] that was implemented in [17]. On the other hand, Benamou, Cotter and Malamut [6] developed and implemented an alternative method based on entropic approximation of optimal transport and the popular Sinkhorn algorithm (see [15], [27]). In [7], the authors have established well-posedness of semi-discrete approximations (for suitably discretized initial conditions) as well as their convergence. Concerning entropic approximation of semi-geostrophic equations, well-posedness and convergence issues are not addressed in [6]. The purpose of our paper is precisely to study these two questions. The paper is organized as follows. In section 2, we recall fundamentals from optimal transport theory, the weak formulation of semi-geostrophic equations and introduce their entropic approximations with regularization parameter $\varepsilon > 0$. We establish well-posedness of these approximations for every $\varepsilon > 0$ in section 3. Section 4 is devoted to convergence as $\varepsilon \rightarrow 0^+$, including the convergence analysis of the explicit discretization scheme recently proposed in [6].

2 Optimal and entropic optimal transport for semi-geostrophic equations

Notations We shall denote by $\mathcal{P}(\mathbb{R}^d)$ the set of Borel probability measures on $\mathbb{R}^d$, by $\mathcal{P}_c(\mathbb{R}^d)$ the set of compactly supported Borel probability measures on $\mathbb{R}^d$, for $R > 0$, B_R denotes the closed ball of radius R of $\mathbb{R}^d$, centered at 0 and $\mathcal{P}(B_R)$ the set of Borel probability measures supported on B_R . For $x \in \mathbb{R}^d$, we denote by $|x|$ the euclidean norm of x and if A is a $d \times d$ matrix, $\|A\|$ stands for the euclidean operator norm of A .

Optimal transport (OT) and weak solutions of the semi-geostrophic system Given $R > 0$, α and μ in $\mathcal{P}(B_R)$, denoting by $\Pi(\alpha, \mu)$ the set of transport plans between α and μ i.e. the set of Borel probability measures on $\mathbb{R}^d \times \mathbb{R}^d$ having α and μ as marginals, the squared-2-Wasserstein distance between α and μ is defined as the value of the quadratic OT problem

$$W_2^2(\alpha, \mu) := \inf_{\gamma \in \Pi(\alpha, \mu)} \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma(dx, dy). \quad (2.1)$$

It is a classical result of Brenier [8] that, as soon as μ is absolutely continuous with respect to the Lebesgue measure, (2.1) admits a unique optimal plan γ which is characterized by $\gamma = (\nabla\varphi, \text{id})_{\#}\mu$ i.e.

$$\int_{\mathbb{R}^d \times \mathbb{R}^d} f(x, y) \gamma(dx, dy) = \int_{\mathbb{R}^d} f(\nabla\varphi(y), y) \mu(dy), \quad \forall f \in C_c(\mathbb{R}^d \times \mathbb{R}^d)$$

with φ convex (and $\nabla\varphi$ unique up to μ -negligible sets). Note in particular that $\nabla\varphi_{\#}\mu = \alpha$ and defining ψ as the Legendre transform of φ :

$$\psi(x) := \sup_{y \in B_R} \{x \cdot y - \varphi(y)\}, \quad \forall x \in \mathbb{R}^d$$

the optimal plan γ is supported by pairs (x, y) for which $y \in \partial\psi(x)$ (where $\partial\psi(x)$ denotes the subdifferential of the convex function ψ at x , see [28]). In particular, if we disintegrate γ with respect to its first marginal α :

$$\gamma(dx, dy) = \alpha(dx) \gamma(dy|x)$$

so that $\gamma(\cdot|x)$ is a probability measure on B_R , its conditional expectation

$$\int_{\mathbb{R}^d} y \gamma(dy|x)$$

belongs to $\partial\psi(x)$ by convexity of $\partial\psi(x)$. Note also that ψ can be seen, at least formally, as a weak solution of the Monge-Ampère equation

$$\det(D^2\psi) \mu(\nabla\psi) = \alpha.$$

Let us now fix $R_0 > 0$, $\mu_0 \in \mathcal{P}(B_{R_0})$, α_0 in $\mathcal{P}(B_{R_0})$; let A be a $d \times d$ matrix and $T > 0$ be a time-horizon. We are interested in the following evolution problem for a curve of probability measures $\alpha: t \in [0, T] \mapsto \alpha_t \in \mathcal{P}_c(\mathbb{R}^d)$:

$$\partial_t \alpha + \operatorname{div}(\alpha A(\operatorname{id} - \nabla \psi)) = 0, \quad \alpha(0, \cdot) = \alpha_0, \quad \det(D^2 \psi_t) \mu_0(\nabla \psi_t) = \alpha_t, \quad \psi_t \text{ convex.} \quad (2.2)$$

Of course, for $d = 3$, μ_0 the uniform probability measure on Ω and $A = J$, we recover the initial problem (1.1)-(1.2) after normalizing all measures by dividing them by $|\Omega|$. In view of the previous discussion, it is natural to define weak solutions of (2.2) as follows. A weak solution of (2.2) on $[0, T] \times \mathbb{R}^d$, is a continuous for W_2 curve of probability measures $t \in [0, T] \mapsto \alpha_t \in \mathcal{P}_c(\mathbb{R}^d)$ such that:

- $\operatorname{spt}(\alpha_t) \subset B_{2R_0 e^{\|A\|T}}$ for every $t \in [0, T]$ (which by Grönwall's lemma, is consistent with the linear growth of the velocity field: $|A(x - \nabla \psi(x))| \leq \|A\|(|x| + R_0)$ and the fact that the initial condition α_0 is supported in B_{R_0}),
- for every $f \in C^1([0, T] \times \mathbb{R}^d)$, one has

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t(dx) dt - \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} Ay \cdot \nabla f(t, x) \gamma_t(dx, dy) dt \\ = \int_{\mathbb{R}^d} f(T, x) \alpha_T(dx) - \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx), \end{aligned} \quad (2.3)$$

where γ_t is an optimal plan between α_t and μ_0 i.e. $\gamma_t \in \Pi(\alpha_t, \mu_0)$ and

$$W_2^2(\alpha_t, \mu_0) = \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_t(dx, dy), \quad \text{for a.e. } t \in [0, T]. \quad (2.4)$$

Note that we have not imposed that μ_0 is absolutely continuous with respect to the Lebesgue measure here (so that there may not exist optimal transport maps between μ_0 and α_t which is the reason the weak formulation above has been written in terms of possibly non unique-optimal plans).

Entropic OT and entropic semi-geostrophic equations Given $\varepsilon > 0$, α and μ in $\mathcal{P}_c(\mathbb{R}^d)$, the entropic regularization of the quadratic OT problem (2.1) reads

$$\operatorname{OT}_\varepsilon(\alpha, \mu) := \inf_{\gamma \in \Pi(\alpha, \mu)} \left\{ \frac{1}{2} \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma(dx, dy) + \varepsilon H(\gamma | \alpha \otimes \mu) \right\} \quad (2.5)$$

where $H(p|q)$ denotes the relative entropy of p with respect to q :

$$H(p|q) = \begin{cases} \int_{\mathbb{R}^d} \log\left(\frac{dp}{dq}(x)\right) p(dx) & \text{if } p \ll q, \\ +\infty & \text{otherwise.} \end{cases}$$

There exists a unique optimal plan γ^ε for $\text{OT}_\varepsilon(\alpha, \mu)$ and it is well-known that γ^ε has the Gibbs form

$$\gamma^\varepsilon(dx, dy) = \exp\left(-\frac{|x-y|^2}{2\varepsilon} + \frac{u^\varepsilon(y) + v^\varepsilon(x)}{\varepsilon}\right) \alpha(dx) \mu(dy) \quad (2.6)$$

where the potentials u^ε and v^ε are such that $\gamma^\varepsilon \in \Pi(\alpha, \mu)$ i.e. satisfy the so-called Schrödinger system

$$v^\varepsilon(x) = -\varepsilon \log\left(\int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{2\varepsilon} + \frac{u^\varepsilon(y)}{\varepsilon}} \mu(dy)\right) \text{ for } \alpha\text{-a.e. } x, \quad (2.7)$$

and

$$u^\varepsilon(y) = -\varepsilon \log\left(\int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{2\varepsilon} + \frac{v^\varepsilon(x)}{\varepsilon}} \alpha(dx)\right) \text{ for } \mu\text{-a.e. } y. \quad (2.8)$$

These potentials are called Schrödinger potentials for the entropic optimal transport problem between α and μ . For an overview of entropic optimal transport, we refer the reader to [23], the lecture notes [26] and the references therein. Note that formulas (2.7) and (2.8) can be extended to define smooth maps on the whole of $\mathbb{R}^d$ (which are defined uniquely up to additive constants) and that disintegrating the optimal entropic plan γ^ε as

$$\gamma^\varepsilon(dx, dy) = \alpha(dx) \gamma^\varepsilon(dy|x)$$

one has for every $x \in \mathbb{R}^d$

$$\nabla v^\varepsilon(x) = \frac{\int_{\mathbb{R}^d} (x-y) e^{-\frac{|x-y|^2}{2\varepsilon} + \frac{u^\varepsilon(y)}{\varepsilon}} \mu(dy)}{\int_{\mathbb{R}^d} e^{-\frac{|x-y|^2}{2\varepsilon} + \frac{u^\varepsilon(y)}{\varepsilon}} \mu(dy)} = x - \int_{\mathbb{R}^d} y \gamma^\varepsilon(dy|x) \quad (2.9)$$

and

$$D^2 v^\varepsilon(x) = \text{id} - \varepsilon^{-1} \left(\int_{\mathbb{R}^d} y \otimes y \gamma^\varepsilon(dy|x) - \int_{\mathbb{R}^d} y \gamma^\varepsilon(dy|x) \otimes \int_{\mathbb{R}^d} y \gamma^\varepsilon(dy|x) \right). \quad (2.10)$$

Before defining the entropic regularization of the semi-geostrophic system, let us recall two results that will be useful in the following. The first result follows from Proposition 3.1 of [10] which gives an error estimate of the form $\text{OT}_\varepsilon - \frac{1}{2} W_2^2 = O(\varepsilon |\log(\varepsilon)|)$ or the (more precise) results from [25] where an $O(\varepsilon)$ suboptimality estimate for entropic plans is established. A non quantitative consequence of these results can be stated as:

Proposition 2.1. *Let $R > 0$ and for $\alpha, \beta \in \mathcal{P}(B_R)^2$, denote by $\gamma_{\alpha, \beta}^\varepsilon$ the solution of the entropic optimal transport problem between α and β . Then $\int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_{\alpha, \beta}^\varepsilon(dx, dy)$ converges to $W_2^2(\alpha, \beta)$ uniformly in $\alpha, \beta \in \mathcal{P}(B_R)^2$ as $\varepsilon \rightarrow 0$.*

The second result concerns the stability of the Schrödinger potentials with respect to the marginals¹ and follows from Theorem 1.1 of [9]:

Proposition 2.2. *Let $R > 0$ and $\mu_0 \in \mathcal{P}(B_R)$. For $\alpha \in \mathcal{P}(B_R)$, let $v^\varepsilon[\alpha]$ be the Schrödinger potential for the entropic optimal transport problem between α and μ_0 . Then, there is a constant $\Delta(\varepsilon, R)$ depending on ε and R such that for every $\alpha_1, \alpha_2 \in \mathcal{P}(B_R)^2$, we have*

$$\|\nabla v^\varepsilon[\alpha_1] - \nabla v^\varepsilon[\alpha_2]\|_{L^\infty(B_R)} \leq \Delta(\varepsilon, R) W_2(\alpha_1, \alpha_2). \quad (2.11)$$

Given $T > 0$, $R_0 > 0$, μ_0 and α_0 in $\mathcal{P}(B_{R_0})$, we now consider the following entropic regularization with parameter $\varepsilon > 0$ of (2.2)

$$\partial_t \alpha^\varepsilon + \operatorname{div}(\alpha^\varepsilon A(\nabla v^\varepsilon)) = 0 \text{ in } [0, T] \times \mathbb{R}^d, \quad \alpha^\varepsilon(0, \cdot) = \alpha_0, \quad (2.12)$$

where

$$\nabla v_t^\varepsilon(x) = x - \int_{\mathbb{R}^d} y \gamma_t^\varepsilon(dy|x) \quad (2.13)$$

and γ_t^ε is the solution of $\operatorname{OT}^\varepsilon(\alpha_t^\varepsilon, \mu_0)$:

$$\gamma_t^\varepsilon \in \Pi(\alpha_t^\varepsilon, \mu_0), \quad \operatorname{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0) = \frac{1}{2} \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_t^\varepsilon(dx, dy) + \varepsilon H(\gamma_t^\varepsilon | \alpha_t^\varepsilon \otimes \mu_0). \quad (2.14)$$

Since γ_t^ε has second marginal μ_0 supported on B_{R_0} , the conditional probability $\gamma_t^\varepsilon(\cdot|x)$ is supported on B_{R_0} , as well so that ∇v^ε has controlled linear growth

$$|\nabla v_t^\varepsilon(x)| \leq |x| + R_0, \quad \forall x \in \mathbb{R}^d, \quad \forall t. \quad (2.15)$$

Therefore one defines weak solutions of (2.12)-(2.13)-(2.14) in a similar way as we did for (2.2). A weak solution of (2.12)-(2.13)-(2.14) on $[0, T] \times \mathbb{R}^d$, is a continuous for W_2 curve of probability measures $t \in [0, T] \mapsto \alpha_t^\varepsilon \in \mathcal{P}_c(\mathbb{R}^d)$ such that:

- $\operatorname{spt}(\alpha_t^\varepsilon) \subset B_{2R_0 e^{\|A\|T}}$ for every $t \in [0, T]$,

¹It is worth mentioning that the constant $\Delta(\varepsilon, R)$ in (2.11) derived from the analysis of [9] scales exponentially badly with ε . Interestingly, in the very recent paper [16] close (but not obviously applicable to our context) results are obtained with much better constants of the order of $R^2 \varepsilon^{-1}$.

- for every $f \in C^1([0, T] \times \mathbb{R}^d)$, one has

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t^\varepsilon(dx) dt - \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} Ay \cdot \nabla f(t, x) \gamma_t^\varepsilon(dx, dy) dt \\ = \int_{\mathbb{R}^d} f(T, x) \alpha_T^\varepsilon(dx) - \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx), \end{aligned} \quad (2.16)$$

where for a.e. $t \in [0, T]$, γ_t^ε is the solution of $\text{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0)$ i.e. (2.14) holds.

3 Well-posedness for fixed $\varepsilon > 0$

To prove well-posedness of entropic semi-geostrophic equations, we will show that these equations enjoy nice Lipschitz properties (detailed in paragraph 3.1 below) for which an elementary fixed-point argument can be used.

3.1 A fixed-point argument

Consider a map $B : \alpha \in \mathcal{P}_c(\mathbb{R}^d) \mapsto B[\alpha] \in C(\mathbb{R}^d, \mathbb{R}^d)$ with the following properties:

- **(H1)** There exists $C > 0$ such that

$$|B[\alpha](x)| \leq C(1 + |x|), \quad \forall (x, \alpha) \in \mathbb{R}^d \times \mathcal{P}_c(\mathbb{R}^d). \quad (3.1)$$

- **(H2)** For every $R > 0$

$$K_R := \sup\{\text{Lip}(B[\alpha], B_R), \alpha \in \mathcal{P}(B_R)\} < +\infty. \quad (3.2)$$

- **(H3)** For every $R > 0$

$$M_R := \sup \left\{ \frac{\|B[\alpha^1] - B[\alpha^2]\|_{L^\infty(B_R)}}{W_2(\alpha^1, \alpha^2)}, (\alpha^1, \alpha^2) \in \mathcal{P}(B_R)^2, \alpha^1 \neq \alpha^2 \right\} < +\infty. \quad (3.3)$$

Lemma 3.1. *Let $B : \alpha \in \mathcal{P}_c(\mathbb{R}^d) \mapsto B[\alpha] \in C(\mathbb{R}^d, \mathbb{R}^d)$ satisfy **(H1)**-**(H2)**-**(H3)**, $R_0 > 0$, $\alpha_0 \in \mathcal{P}(B_{R_0})$ and $T > 0$. Setting $R_T := (R_0 + 1)e^{CT}$, there exists a unique curve $t \in [0, T] \mapsto \alpha_t \in \mathcal{P}(B_{R_T})$ which solves*

$$\partial_t \alpha + \text{div}(\alpha B[\alpha]) = 0, \quad \alpha(0, \cdot) = \alpha_0, \quad (3.4)$$

in the weak sense on $[0, T] \times \mathbb{R}^d$.

Proof. Set $K = K_{R_T}$, $M = M_{R_T}$ (see (3.2) and (3.3)) and

$$\lambda := \frac{5M}{2} + K. \quad (3.5)$$

Define

$$E_T := C([0, T], (\mathcal{P}(B_{R_T}), W_2))$$

which, equipped with the distance

$$\text{dist}(\alpha^1, \alpha^2) := \sup_{t \in [0, T]} e^{-\lambda t} W_2(\alpha_t^1, \alpha_t^2), \quad (\alpha^1, \alpha^2) = (\alpha_t^1, \alpha_t^2)_{t \in [0, T]} \in E_T^2$$

is a complete metric space. By well-known arguments on the continuity equation (see Chapter 8 in [4]), our assumptions on B imply that $\alpha \in E_T$ solves (3.4) if and only if

$$\alpha = \Phi_{\alpha_0}(\alpha) \text{ with } \Phi_{\alpha_0}(\alpha)_t := X_t^\alpha \# \alpha_0, \quad t \in [0, T]$$

where X_t^α is the (globally well-defined) flow of $B[\alpha]$:

$$\frac{d}{dt} X_t^\alpha(x) = B[\alpha_t](X_t^\alpha(x)), \quad X_0^\alpha(x) = x, \quad (t, x) \in [0, T] \times \mathbb{R}^d. \quad (3.6)$$

By Grönwall's Lemma and (3.1) Φ_{α_0} is a self map of E_T , we shall now prove that it is a contraction. Let $(\alpha^1, \alpha^2) \in E_T^2$, to shorten notation set $B^i(t, x) = B[\alpha_t^i](x)$, $i = 1, 2$ and let X_t^1, X_t^2 denote the flows of B^1 and B^2 respectively. Then, we first obviously have

$$W_2^2(\Phi_{\alpha_0}(\alpha^1)_t, \Phi_{\alpha_0}(\alpha^2)_t) = W_2^2(X_t^1 \# \alpha_0, X_t^2 \# \alpha_0) \leq \int_{\mathbb{R}^d} |X_t^1(x) - X_t^2(x)|^2 \alpha_0(dx) \quad (3.7)$$

Next we observe that for fixed $x \in B_{R_0}$,

$$\begin{aligned} \frac{d}{dt} |X_t^1(x) - X_t^2(x)|^2 &= 2(X_t^1(x) - X_t^2(x)) \cdot (B^1(t, X_t^1(x)) - B^2(t, X_t^2(x))) \\ &= 2(X_t^1(x) - X_t^2(x)) \cdot (B^1(t, X_t^1(x)) - B^1(t, X_t^2(x))) \\ &\quad + 2(X_t^1(x) - X_t^2(x)) \cdot (B^1(t, X_t^2(x)) - B^2(t, X_t^2(x))) \\ &\leq 2K |X_t^1(x) - X_t^2(x)|^2 + 2M W_2(\alpha_t^1, \alpha_t^2) |X_t^1(x) - X_t^2(x)| \\ &\leq (2K + M) |X_t^1(x) - X_t^2(x)|^2 + M \text{dist}^2(\alpha^1, \alpha^2) e^{2\lambda t} \end{aligned}$$

where we have used (3.2)-(3.3) and Cauchy-Schwarz for the first inequality and Young's inequality and the definition of dist in the last line. Thanks to Grönwall's Lemma, we get by our choice of λ in (3.5):

$$|X_t^1(x) - X_t^2(x)|^2 e^{-2\lambda t} \leq \frac{M \text{dist}^2(\alpha^1, \alpha^2)}{2\lambda - 2K - M} = \frac{\text{dist}^2(\alpha^1, \alpha^2)}{4}.$$

Together with (3.7), integrating the previous inequality with respect to α_0 yields

$$\text{dist}^2(\Phi_{\alpha_0}(\alpha^1), \Phi_{\alpha_0}(\alpha^2)) = \sup_{t \in [0, T]} e^{-2\lambda t} W_2^2(\Phi_{\alpha_0}(\alpha^1)_t, \Phi_{\alpha_0}(\alpha^2)_t) \leq \frac{\text{dist}^2(\alpha^1, \alpha^2)}{4}$$

which shows that Φ is $\frac{1}{2}$ -Lipschitz hence a contraction for dist . The existence and uniqueness of a fixed-point follows from the Banach-Picard fixed-point Theorem which completes the proof. $\square$

Remark 3.2. The above proof also straightforwardly implies the Lipschitz dependence of the solution of (3.4) with respect to the initial condition. Indeed, let α_0 and $\tilde{\alpha}_0$ be in $\mathcal{P}(B_{R_0})$ $t \in [0, T] \mapsto \alpha_t$ and $t \in [0, T] \mapsto \tilde{\alpha}_t$ denote the solution of (3.4) with respective initial conditions α_0 and $\tilde{\alpha}_0$. Then, defining K , M , λ , dist , Φ_{α_0} and $\Phi_{\tilde{\alpha}_0}$ as in the proof of Lemma 3.1, we have thanks to the triangle inequality and the fact that Φ_{α_0} is $\frac{1}{2}$ -Lipschitz

$$\begin{aligned} \text{dist}(\alpha, \tilde{\alpha}) &= \text{dist}(\Phi_{\alpha_0}(\alpha), \Phi_{\tilde{\alpha}_0}(\tilde{\alpha})) \leq \text{dist}(\Phi_{\alpha_0}(\alpha), \Phi_{\alpha_0}(\tilde{\alpha})) + \text{dist}(\Phi_{\alpha_0}(\tilde{\alpha}), \Phi_{\tilde{\alpha}_0}(\tilde{\alpha})) \\ &\leq \frac{1}{2} \text{dist}(\alpha, \tilde{\alpha}) + \text{dist}(\Phi_{\alpha_0}(\tilde{\alpha}), \Phi_{\tilde{\alpha}_0}(\tilde{\alpha})) \end{aligned}$$

Hence

$$\text{dist}(\alpha, \tilde{\alpha}) \leq 2 \text{dist}(\Phi_{\alpha_0}(\tilde{\alpha}), \Phi_{\tilde{\alpha}_0}(\tilde{\alpha})) \leq 2W_2(\alpha_0, \tilde{\alpha}_0) \sup_{t \in [0, T]} e^{-\lambda t} \text{Lip}(X_t^{\tilde{\alpha}}, B_{R_T})$$

but it is straightforward to deduce from **(H2)** and Grönwall's Lemma, that $\text{Lip}(X_t^{\tilde{\alpha}}, B_{R_T}) \leq e^{Kt}$ and since $\lambda - K = \frac{5M}{2} \geq 0$ we arrive at

$$\text{dist}(\alpha, \tilde{\alpha}) \leq 2W_2(\alpha_0, \tilde{\alpha}_0). \quad (3.8)$$

3.2 Well-posedness of entropic semi-geostrophic equations

The fact that (2.12)-(2.13)-(2.14) is well-posed then directly follows from Lemma 3.1 and regularity properties of entropic OT:

Theorem 3.3. *Given $T > 0$, $R_0 > 0$, α_0 and μ_0 in $\mathcal{P}(B_{R_0})$, for every $\varepsilon > 0$, the system (2.12)-(2.13)-(2.14) admits a unique weak solution on $[0, T] \times \mathbb{R}^d$.*

Proof. Given $\alpha \in \mathcal{P}_c(\mathbb{R}^d)$, denote by γ^ε the solution of $\text{OT}_\varepsilon(\alpha, \mu_0)$ (equivalently solve the Schrödinger system (2.7)-(2.8) to obtain the potential v^ε) and set

$$B^\varepsilon[\alpha](x) := A(x - \int_{\mathbb{R}^d} y \gamma^\varepsilon(dy|x)) = A(\nabla v^\varepsilon(x)), \quad \forall x \in \mathbb{R}^d. \quad (3.9)$$

Let us show that the map $\alpha \mapsto B^\varepsilon[\alpha]$ satisfies **(H1)**-**(H2)**-**(H3)**. Concerning **(H1)**, the linear growth condition (3.1) follows from the fact that $\gamma^\varepsilon(\cdot|x)$ has support in B_{R_0} , so that $|B^\varepsilon[\alpha](x)| \leq \|A\|(|x| + R_0)$ hence **(H1)** holds with the constant $C = \max(1, R_0)\|A\|$. As for **(H2)**, this also follows from the fact that $\gamma^\varepsilon(\cdot|x)$ has support in B_{R_0} and the expression of the hessian of v^ε in (2.10) which yields the bound (exploding as $\varepsilon \rightarrow 0$)

$$\|DB[\alpha]\| \leq \|A\| \|D^2 v^\varepsilon\| \leq \|A\| (1 + 2\varepsilon^{-1} R_0^2).$$

Therefore **(H2)** holds with the constant $K_R = \|A\| (1 + 2\varepsilon^{-1} R_0^2)$ (depending on ε but not R). Finally, it follows from Proposition 2.2 that B^ε satisfies **(H3)** with the constant $M_R = \Lambda(\varepsilon, R)\|A\|$, $\Lambda(\varepsilon, R)$ being the constant in (2.11). Thanks to Lemma 3.1, we deduce that there exists a unique solution α^ε of the system (2.12)-(2.13)-(2.14) with α_t^ε supported for every $t \in [0, T]$ on the ball of radius $(R_0 + 1)e^{\max(1, R_0)\|A\|T}$ but a direct application of Grönwall's Lemma gives that it has to be supported on the ball of radius $2R_0 e^{\|A\|T}$ as in our initial definition in section 2. $\square$

3.3 On conservation of energy

In the physically relevant case $d = 3$, $A = J$, one can define the (entropically regularized) total energy

$$E_\varepsilon(\alpha) := \text{OT}_\varepsilon(\alpha, \mu_0) + \int_{\mathbb{R}^3} x_3 \alpha.$$

Of course, the potential energy i.e. the second term is preserved along the flow α^ε of the entropic semi-geostrophic equation (obtained by Theorem 3.3), by taking a test function depending on x_3 only, we readily see that the marginal of α^ε in the x_3 -variable is constant in time. As for the conservation of $t \mapsto \text{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0)$, one can argue as follows.

Using a well-known dual formulation (see [26], [22], [23]) of entropic optimal transport (or by a direct computation using (2.7)-(2.8)), given $\beta \in$

$\mathcal{P}_c(\mathbb{R}^3)$, one can also write $\text{OT}_\varepsilon(\beta, \mu_0)$ as the supremum of an unconstrained concave maximization problem

$$\varepsilon + \sup_{u,v} \left\{ \int_{\mathbb{R}^3} u d\mu_0 + \int_{\mathbb{R}^3} v d\beta - \varepsilon \int_{\mathbb{R}^3 \times \mathbb{R}^3} e^{\frac{-|x-y|^2}{2\varepsilon}} e^{\frac{v(x)+u(y)}{\varepsilon}} \beta(dx) \mu_0(dy) \right\}$$

and this supremum is achieved when u and v are Schrödinger potentials between β and μ_0 . In particular, if we denote by $v^\varepsilon = v^\varepsilon[\beta]$ and $u^\varepsilon = u^\varepsilon[\beta]$ these potentials, when η is another compactly supported probability measure, we have

$$\begin{aligned} \text{OT}_\varepsilon(\eta, \mu_0) - \text{OT}_\varepsilon(\beta, \mu_0) &\geq \int_{\mathbb{R}^3} v^\varepsilon(\eta - \beta) \\ &\quad - \varepsilon \int_{\mathbb{R}^3} \left(\int_{\mathbb{R}^3} e^{\frac{-|x-y|^2}{2\varepsilon}} e^{\frac{v^\varepsilon(x)+u^\varepsilon(y)}{\varepsilon}} \mu_0(dy) \right) (\eta - \beta)(dx) \\ &= \int_{\mathbb{R}^3} v^\varepsilon(\eta - \beta) \end{aligned} \tag{3.10}$$

where passing to the last line, we have used the fact that v^ε and u^ε are Schrödinger potentials between β and μ_0 (so that (2.7) holds for $\mu = \mu_0$) and that η and β have same total mass. For t and s in $[0, T]$, applying (3.10) to the measures α_s^ε , α_t^ε and the potential $v_t^\varepsilon = v^\varepsilon[\alpha_t^\varepsilon]$, we get, using the fact that α^ε solves the semi entropic semi-geostrophic equation in the second line, the fact that J is skew-symmetric in the third line, and finally the fact that $\beta \mapsto \nabla v^\varepsilon[\beta]$ satisfies **(H3)** (thanks to Proposition 2.2) and that $\tau \mapsto \alpha_\tau^\varepsilon$ is Lipschitz for W_2 in the last line

$$\begin{aligned} \text{OT}_\varepsilon(\alpha_s^\varepsilon, \mu_0) - \text{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0) &\geq \int_{\mathbb{R}^3} v_t^\varepsilon(\alpha_s^\varepsilon - \alpha_t^\varepsilon) \\ &= \int_t^s \int_{\mathbb{R}^3} \nabla v_t^\varepsilon(x) J(\nabla v_\tau^\varepsilon(x)) \alpha_\tau^\varepsilon(dx) d\tau \\ &= \int_t^s \int_{\mathbb{R}^3} \nabla v_t^\varepsilon(x) J(\nabla v_\tau^\varepsilon(x) - \nabla v_t^\varepsilon(x)) \alpha_\tau^\varepsilon(dx) d\tau \\ &\geq -|s - t| \|\nabla v^\varepsilon\|_{L^\infty(B_{2R_0 e^T})} \sup_{\tau \in [t, s]} \|\nabla v_\tau^\varepsilon - \nabla v_t^\varepsilon\|_{L^\infty(B_{2R_0 e^T})} \\ &\geq -C_\varepsilon (s - t)^2 \end{aligned}$$

which, reversing the role of s and t , yields $\text{OT}_\varepsilon(\alpha_s^\varepsilon, \mu_0) - \text{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0) = O((s - t)^2)$ hence the preservation of $\text{OT}_\varepsilon(\cdot, \mu_0)$ and E_ε along α^ε .

3.4 Discretization

The fixed-point argument of paragraph 3.1 is useful to derive well-posedness for entropic approximations of semi-geostrophic equations as we saw in paragraph 3.2, it is however useless in practice to design numerical simulations. In this paragraph, we therefore aim to discuss the convergence of an explicit scheme for (3.4) which is in line with [6] and where:

- the initial condition is approximated by some empirical measure (which makes pushforward operations explicit)
- the flow of $B[\alpha]$ is discretized in time by its explicit Euler counterpart (for entropic semi-geostrophic equations and for a discrete α , computing $B[\alpha]$ amounts to compute the Schrödinger potential between α and μ_0 which can be done efficiently by Sinkhorn's algorithm as in [6]).

More precisely, given $\alpha_0 \in \mathcal{P}(B_{R_0})$ and $T > 0$, we denote by α the solution of (3.4) obtained as in Lemma 3.1. Given $\tilde{\alpha}_0 \in \mathcal{P}(B_{R_0})$ (which we can think of as a quantized version of α_0), $N \in \mathbb{N}^*$ and $\tau = \frac{T}{N}$ a time step, we consider the sequence of measures α_k^τ , $k = 0, \dots, N-1$ defined recursively by

$$\alpha_0^\tau = \tilde{\alpha}_0, \alpha_{k+1}^\tau := (\text{id} + \tau B[\alpha_k^\tau])_\# \alpha_k^\tau, k = 0, \dots, N-1. \quad (3.11)$$

Note that whenever $\tilde{\alpha}_0$ is an empirical measure so is α_k^τ and that α_k^τ remains supported on B_{R_T} with $R_T = (R_0 + 1)e^{CT}$ and C is the constant appearing in (3.1). Let us finally denote by $\tilde{\alpha}^\tau$ the piecewise constant interpolation $t \in [0, T) \mapsto \tilde{\alpha}_t^\tau$:

$$\tilde{\alpha}_t^\tau = \alpha_k^\tau, t \in [k\tau, (k+1)\tau), k = 0, \dots, N-1. \quad (3.12)$$

Then we have the following error estimate between the solution α of (3.4) and its discretized counterpart $\tilde{\alpha}^\tau$:

Lemma 3.4. *Assuming B satisfies **(H1)**-**(H2)**-**(H3)**, there is a positive constant Λ depending on T , $R_T = (R_0 + 1)e^{CT}$, C , $K = K_{R_T}$ and $M = M_{R_T}$ such that, for α and $\tilde{\alpha}^\tau$ as above, one has*

$$\sup_{t \in [0, T)} W_2(\alpha_t, \tilde{\alpha}_t^\tau) \leq \Lambda(\tau + W_2(\alpha_0, \tilde{\alpha}_0)). \quad (3.13)$$

Proof. For notational simplicity, throughout this proof we just write $R = R_T$. Setting $L := \sup_{\beta \in \mathcal{P}(B_R)} \|B[\beta]\|_{L^\infty(B_R)}$, we first obviously have

$$W_2(\alpha_t, \alpha_s) \leq L|t - s|, (s, t) \in [0, T]^2. \quad (3.14)$$

Hence

$$\sup_{t \in [0, T)} W_2(\alpha_t, \tilde{\alpha}_t^\tau) \leq \max_{k=0, \dots, N} W_2(\alpha_{k\tau}, \alpha_k^\tau) + L\tau. \quad (3.15)$$

For $k = 0, \dots, N$ set $d_k := W_2(\alpha_{k\tau}, \alpha_k^\tau)$. For $k = 0, \dots, N-1$, notice that $\alpha_{(k+1)\tau} = X_{k\#}^\tau \alpha_{k\tau}$ where $X_k^\tau := Y_{(k+1)\tau}$ and

$$\frac{d}{ds} Y_s(x) = B[\alpha_s](Y_s(x)), \quad Y_{k\tau}(x) = x$$

so that

$$X_k^\tau(x) = x + \tau B[\alpha_{k\tau}](x) + \int_{k\tau}^{(k+1)\tau} (B[\alpha_s](Y_s(x)) - B[\alpha_{k\tau}](x)) ds$$

using **(H2)**-**(H3)** and the fact that $|Y_s(x) - x| \leq L(s - k\tau)$ for every $(x, s) \in B_R \times [k\tau, (k+1)\tau]$, we arrive at

$$\|X_k^\tau - (\text{id} + \tau B[\alpha_{k\tau}])\|_{L^\infty(B_R)} \leq (K + M)L\tau^2. \quad (3.16)$$

By the triangle inequality, we have

$$\begin{aligned} d_{k+1} &= W_2(X_{k\#}^\tau \alpha_{k\tau}, (\text{id} + \tau B[\alpha_k^\tau])_\# \alpha_k^\tau) \\ &\leq W_2(X_{k\#}^\tau \alpha_{k\tau}, (\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_{k\tau}) \\ &\quad + W_2((\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_{k\tau}, (\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_k^\tau) \\ &\quad + W_2((\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_k^\tau, (\text{id} + \tau B[\alpha_k^\tau])_\# \alpha_k^\tau). \end{aligned}$$

Firstly, (3.16) yields

$$W_2(X_{k\#}^\tau \alpha_{k\tau}, (\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_{k\tau}) \leq \|X_k^\tau - (\text{id} + \tau B[\alpha_{k\tau}])\|_{L^\infty(B_R)} \leq (K + M)L\tau^2.$$

Secondly, assumption **(H2)** entails

$$\begin{aligned} W_2((\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_{k\tau}, (\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_k^\tau) &\leq \text{Lip}(\text{id} + \tau B[\alpha_{k\tau}], B_R) W_2(\alpha_{k\tau}, \alpha_k^\tau) \\ &\leq (1 + K\tau) d_k. \end{aligned}$$

Finally, we deduce from **(H3)**

$$W_2((\text{id} + \tau B[\alpha_{k\tau}])_\# \alpha_k^\tau, (\text{id} + \tau B[\alpha_k^\tau])_\# \alpha_k^\tau) \leq \tau \|B[\alpha_{k\tau}] - B[\alpha_k^\tau]\|_{L^\infty(B_R)} \leq M\tau d_k$$

which enables us to conclude that

$$d_{k+1} \leq (K + M)L\tau^2 + (1 + (M + K)\tau) d_k$$

which, by the discrete Grönwall's Lemma, yields that for $k = 0, \dots, N$

$$d_k \leq (1 + (K + M)\tau)^k (L\tau + d_0) \leq e^{(K+M)T} (L\tau + W_2(\alpha_0, \tilde{\alpha}_0))$$

together with (3.15), this proves the desired inequality (3.13). $\square$

Remark 3.5. If we take $\tilde{\alpha}_0 = \alpha_0$ in Lemma 3.4, the convergence of the theoretical Euler scheme is a well known fact, even in frameworks with much less regularity (see [11]). However, the interest of lemma 3.4 is to give a convergence rate that is linear in τ which is natural to expect in the case of the first-order Euler scheme with enough regularity. Since [9] provides bounds for higher derivatives of the entropic potentials, the proof could also be adapted to higher order explicit schemes such as Runge-Kutta and provide better convergence rates.

4 Convergence to a weak solution as $\varepsilon \rightarrow 0^+$

4.1 Convergence of continuous trajectories

For fixed $T > 0$ and $\varepsilon > 0$, let $\alpha^\varepsilon \in C([0, T], (\mathcal{P}(B_{2R_0 e^{\|A\|T}}), W_2))$ be the unique weak solution of (2.12)-(2.13)-(2.14) obtained as in Theorem 3.3. To simplify notation, let us set $R := 2R_0 e^{\|A\|T}$.

Since the velocity $A(\nabla v^\varepsilon)$ can be bounded in $L^\infty(B_R)$ uniformly in ε , there is a constant $\kappa > 0$ such that

$$W_2(\alpha_t^\varepsilon, \alpha_s^\varepsilon) \leq \kappa |t - s|, \quad \forall \varepsilon > 0, \quad \forall (s, t) \in [0, T]^2.$$

Thanks to Arzela-Ascoli Theorem, passing to a vanishing sequence $\varepsilon_n \rightarrow 0$ if necessary, one may assume that, for some $\alpha = (\alpha_t)_{t \in [0, T]} \in C([0, T], (\mathcal{P}(B_R), W_2))$, one has

$$\sup_{t \in [0, T]} W_2(\alpha_t^\varepsilon, \alpha_t) \rightarrow 0 \text{ as } \varepsilon \rightarrow 0^+. \quad (4.1)$$

Our aim is to show that this cluster point α is a weak solution of the unregularized semi-geostrophic like system (2.2). By the very definition of α^ε , for $f \in C^1([0, T] \times \mathbb{R}^d)$, one has

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t^\varepsilon(dx) dt - \int_{\mathbb{R}^d} f(T, x) \alpha_T^\varepsilon(dx) + \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx) \\ = \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} Ay \cdot \nabla f(t, x) \gamma_t^\varepsilon(dx, dy) dt \end{aligned} \quad (4.2)$$

where for a.e. $t \in [0, T]$, γ_t^ε is the solution of $\text{OT}_\varepsilon(\alpha_t^\varepsilon, \mu_0)$. Obviously the left-hand side of (4.2) converges as $\varepsilon \rightarrow 0^+$ to

$$\int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t(dx) dt - \int_{\mathbb{R}^d} f(T, x) \alpha_T(dx) + \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx)$$

As for the right-hand side, by Banach-Alaoglu's Theorem, one may assume that the family of measures $\gamma_t^\varepsilon(dx, dy) \otimes dt$ weakly $*$ converges as $\varepsilon \rightarrow 0^+$ to some measure θ on $B_R^2 \times [0, T]$, since weak $*$ convergence implies weak $*$ convergence of marginals and $\gamma_t^\varepsilon \in \Pi(\alpha_t^\varepsilon, \mu_0)$ for a.e. $t \in [0, T]$, one has

$$\theta(dx, dy, dt) = \gamma_t(dx, dy) \otimes dt \text{ with } \gamma_t \in \Pi(\alpha_t, \mu_0) \text{ for a.e. } t \in [0, T]$$

and then

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t(dx) dt - \int_{\mathbb{R}^d} f(T, x) \alpha_T(dx) + \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx) \\ = \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} Ay \cdot \nabla f(t, x) \gamma_t(dx, dy) dt. \end{aligned}$$

So, to establish that α is a weak solution of (2.2), it remains to show that γ_t is an optimal transport plan between α_t and μ_0 for a.e. $t \in [0, T]$. Since α_t^ε is supported on B_R for all $t \in [0, T]$, by Proposition 2.1, $\int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_t^\varepsilon(dx, dy) - W_2^2(\alpha_t^\varepsilon, \mu_0)$ converges to 0 uniformly in $t \in [0, T]$. Thanks to (4.1), $W_2^2(\alpha_t^\varepsilon, \mu_0) \rightarrow W_2^2(\alpha_t, \mu_0)$ also uniformly in t , so that

$$\begin{aligned} \int_0^T W_2^2(\alpha_t, \mu_0) dt &= \lim_{\varepsilon \rightarrow 0} \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_t^\varepsilon(dx, dy) dt \\ &= \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} |x - y|^2 \gamma_t(dx, dy) dt \end{aligned}$$

where the second line follows from the weak $*$ convergence of $\gamma_t^\varepsilon(dx, dy) \otimes dt$ to $\gamma_t(dx, dy) \otimes dt$, and then since $\gamma_t \in \Pi(\alpha_t, \mu_0)$, for a.e. $t \in [0, T]$, this shows that (2.4) holds so that α is a weak solution of (2.2). In other words, we have shown the following:

Theorem 4.1. *Cluster points as $\varepsilon \rightarrow 0$ of weak solutions of (2.12)-(2.13)-(2.14) are weak solutions of (2.2).*

Remark 4.2. Note that this gives yet another proof of existence of weak solutions of semi-geostrophic equations for compactly supported initial data by entropic approximation. When $d = 3$ and $A = J$, combining the considerations of paragraph 3.3 with the convergence of OT_ε to W_2 , one can readily check that a cluster point α obtained as above, conserves the energy $W_2(\alpha_t, \mu_0)$ (as well as the potential energy of course). This property is actually already well-known for all weak solutions, see [3].

4.2 Convergence of discretizations

We finally consider the case where we both regularize the semi-geostrophic equation with an entropy i.e. replace W_2^2 by OT_ε with small ε and approximate the solution of (2.12)-(2.13)-(2.14) by using an explicit Euler scheme with time step τ and quantizing the initial condition by replacing α_0 by some discrete measure $\tilde{\alpha}_0$ as in paragraph 3.4. Combining Lemma 3.13 and Theorem 4.1, one easily gets that when letting first $\tau + W_2(\alpha_0, \tilde{\alpha}_0)$ tend to 0 and then $\varepsilon \rightarrow 0$, we obtain (along a subsequence) convergence to a weak solution of (2.2). This is of little use in practice to guarantee convergence of the scheme proposed in [6], so we consider the situation where we let all parameters vanish at the same time in an arbitrary manner, i.e. for $\varepsilon > 0$, we consider a time step $\tau_\varepsilon > 0$ with $T = N_\varepsilon \tau_\varepsilon$ and a quantized approximation of the initial $\alpha_0 \in \mathcal{P}(B_{R_0})$ and of the reference measure $\mu_0 \in \mathcal{P}(B_{R_0})$

$$\tilde{\alpha}_0^\varepsilon := \frac{1}{M_\varepsilon} \sum_{i=1}^{M_\varepsilon} \delta_{x_i^\varepsilon}, \quad x_i^\varepsilon \in B_{R_0}; \quad \tilde{\mu}_0^\varepsilon := \frac{1}{M_\varepsilon} \sum_{i=1}^{M_\varepsilon} \delta_{y_i^\varepsilon}, \quad y_i^\varepsilon \in B_{R_0},$$

and assume that

$$\tau_\varepsilon + W_2(\alpha_0, \tilde{\alpha}_0^\varepsilon) + W_2(\mu_0, \tilde{\mu}_0^\varepsilon) \rightarrow 0, \quad \text{as } \varepsilon \rightarrow 0^+. \quad (4.3)$$

We then construct a piecewise constant curve of measures $t \in [0, T] \mapsto \tilde{\alpha}_t^\varepsilon$ by an explicit Euler scheme as in 3.4, i.e.:

$$\tilde{\alpha}_t^\varepsilon = \alpha_k^\varepsilon, \quad t \in [k\tau_\varepsilon, (k+1)\tau_\varepsilon), \quad k = 0, \dots, N_\varepsilon - 1$$

with

$$\alpha_0^\varepsilon = \tilde{\alpha}_0^\varepsilon, \quad \alpha_{k+1}^\varepsilon = (\text{id} + \tau_\varepsilon B^\varepsilon[\alpha_k^\varepsilon])_\# \alpha_k^\varepsilon, \quad k = 0, \dots, N_\varepsilon - 1$$

where B^ε is defined through the solution of $\text{OT}_\varepsilon(\alpha, \tilde{\mu}_0^\varepsilon)$ as in (3.9). Observing that $W_2(\tilde{\alpha}_t^\varepsilon, \tilde{\alpha}_s^\varepsilon) \leq \kappa(|t - s| + \tau)$ for every t, s in $[0, T]$ and a constant κ independent of ε , passing along a (not relabeled) vanishing sequence $\varepsilon_n \rightarrow 0$, we may assume that for some $\alpha = (\alpha_t)_{t \in [0, T]} \in C([0, T], (\mathcal{P}(B_R), W_2))$ (where we recall that we have set $R := 2R_0 e^{\|A\|T}$) one has

$$\sup_{t \in [0, T]} W_2(\tilde{\alpha}_t^\varepsilon, \alpha_t) \rightarrow 0 \quad \text{as } \varepsilon \rightarrow 0^+, \quad (4.4)$$

and $W_2(\alpha_t, \alpha_s) \leq \kappa|t - s|$, for all s and t in $[0, T]$. We then have the following convergence result, which shows that cluster points of the previous approximations are weak solutions of (2.2):

Theorem 4.3. *If α is obtained as a cluster point of the discretized entropic regularization $(\tilde{\alpha}_t^\varepsilon)_{t \in [0, T]}$ i.e. such that (4.4) holds, then α is a weak solution of (2.2).*

Proof. Let $f \in C^1([0, T] \times \mathbb{R}^d)$, observe that

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} \partial_t f \tilde{\alpha}_t^\varepsilon &= \sum_{k=0}^{N_\varepsilon-1} \int_{\mathbb{R}^d} \int_{k\tau_\varepsilon}^{(k+1)\tau_\varepsilon} \partial_t f \alpha_k^\varepsilon = \sum_{k=0}^{N_\varepsilon-1} \int_{\mathbb{R}^d} (f((k+1)\tau_\varepsilon, \cdot) - f(k\tau_\varepsilon, \cdot)) \alpha_k^\varepsilon \\ &= \sum_{k=1}^{N_\varepsilon-1} \int_{\mathbb{R}^d} f(k\tau_\varepsilon, \cdot) (\alpha_{k-1}^\varepsilon - \alpha_k^\varepsilon) + \int_{\mathbb{R}^d} f(T, \cdot) \alpha_{N-1}^\varepsilon - \int_{\mathbb{R}^d} f(0, \cdot) \alpha_0^\varepsilon \end{aligned} \quad (4.5)$$

note that the last two terms in (4.5) converge as $\varepsilon \rightarrow 0$ respectively to $\int_{\mathbb{R}^d} f(T, \cdot) \alpha_T$ and $-\int_{\mathbb{R}^d} f(0, \cdot) \alpha_0$. Setting $B_k^\varepsilon = B^\varepsilon[\alpha_k^\varepsilon]$ and denoting by γ_{k-1}^ε the solution of $\text{OT}_\varepsilon(\alpha_{k-1}^\varepsilon, \tilde{\mu}_0^\varepsilon)$ and using the fact that $\alpha_k^\varepsilon = (\text{id} + \tau_\varepsilon B_k^\varepsilon)_\# \alpha_{k-1}^\varepsilon$, enables to rewrite

$$\begin{aligned} \int_{\mathbb{R}^d} f(k\tau_\varepsilon, \cdot) (\alpha_{k-1}^\varepsilon - \alpha_k^\varepsilon) &= \int_{\mathbb{R}^d} (f(k\tau_\varepsilon, x) - f(k\tau_\varepsilon, x + \tau_\varepsilon B_{k-1}^\varepsilon(x))) \alpha_{k-1}^\varepsilon(dx) \\ &= -\tau_\varepsilon \int_{\mathbb{R}^d} \nabla f(k\tau_\varepsilon, x) \cdot B_{k-1}^\varepsilon(x) \alpha_{k-1}^\varepsilon(dx) + o(\tau_\varepsilon) \\ &= \int_{(k-1)\tau_\varepsilon}^{k\tau_\varepsilon} \int_{\mathbb{R}^d \times \mathbb{R}^d} \nabla f(t, x) \cdot A(y-x) \gamma_{k-1}^\varepsilon(dx, dy) dt + o(\tau_\varepsilon). \end{aligned}$$

Considering the piecewise constant curve of plans $t \mapsto \tilde{\gamma}_t^\varepsilon$ defined by $\tilde{\gamma}_t^\varepsilon = \gamma_k^\varepsilon$ for $t \in [k\tau_\varepsilon, (k+1)\tau_\varepsilon)$, recalling that $N_\varepsilon \tau_\varepsilon = T$, we thus have

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} \partial_t f \tilde{\alpha}_t^\varepsilon &= \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} \nabla f(t, x) \cdot A(y-x) \tilde{\gamma}_t^\varepsilon(dx, dy) dt \\ &\quad + \int_{\mathbb{R}^d} f(T, x) \alpha_T(dx) - \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx) + o(1). \end{aligned} \quad (4.6)$$

As in paragraph 4.1, we may assume (possibly after an extraction) that $\tilde{\gamma}_t^\varepsilon(dx, dy) \otimes dt$ weakly $*$ converge as $\varepsilon \rightarrow 0^+$ to some measure of the form $\gamma_t(dx, dy) \otimes dt$. Then, exactly as in paragraph 4.1, Proposition 2.1 ensures that for a.e. t , $\gamma_t \in \Pi(\alpha_t, \mu_0)$ is an optimal transport plan between α_t and μ_0 i.e. satisfies (2.4). Letting $\varepsilon \rightarrow 0^+$ in (4.6), thanks to (4.4) and $\gamma_t \in \Pi(\alpha_t, \mu_0)$, we get

$$\begin{aligned} \int_0^T \int_{\mathbb{R}^d} [\partial_t f + Ax \cdot \nabla f] \alpha_t &= \int_0^T \int_{\mathbb{R}^d \times \mathbb{R}^d} \nabla f(t, x) \cdot Ay \gamma_t(dx, dy) dt \\ &\quad + \int_{\mathbb{R}^d} f(T, x) \alpha_T(dx) - \int_{\mathbb{R}^d} f(0, x) \alpha_0(dx) \end{aligned}$$

and since γ_t is an optimal transport plan between α_t and μ_0 , α is a weak solution of (2.2). $\square$

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